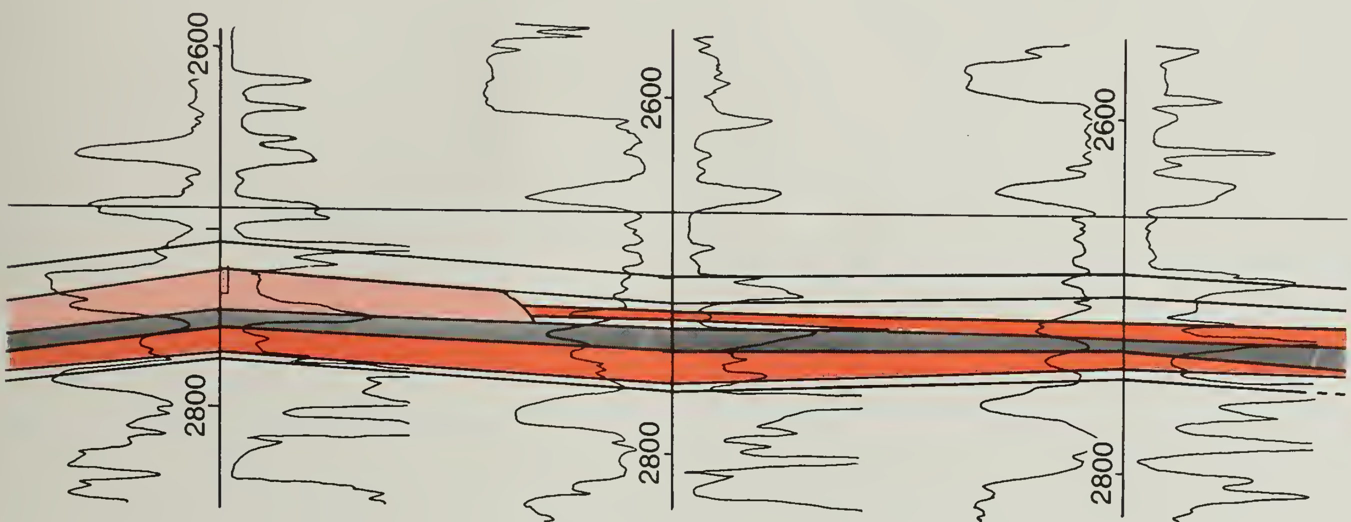
Reservoir Heterogeneity and Improved Oil Recovery of the Aux Vases (Mississippian) Formation at King Field, Jefferson County, Illinois

Hannes E. Leetaru



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ILLINOIS STATE GEOLOGICAL SURVEY
Department of Energy and Natural Resources

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ABSTRACT

King Field, located in Jefferson County, Illinois, was discovered in 1942. The trapping mechanism is structurally and stratigraphically controlled, with the principal production from sandstone and limestone lithofacies in the Mississippian Aux Vases Formation at a depth of about 2,750 feet. The field has 40 feet of anticlinal closure and is 3 miles long and 1.5 miles wide. More than 163 wells, including 108 oil wells, have been drilled on a 10-acre spacing.

The Aux Vases Formation at King Field averages 50 feet thick. Porous and permeable reservoir sandstones are rarely thicker than 20 feet and are typically lenticular. Clean, porous sandstone may, within one well location (660 ft), laterally grade into siltstone, nonporous calcareous sandstone, shale, or limestone.

The Aux Vases Formation at King Field was deposited in a mixed carbonate-siliciclastic, nearshore, shallow marine environment. The large degree of lateral compartmentalization of the reservoir is due to this mixture of carbonate and clastic lithology. The carbonate lithology commonly is not productive and has low permeability; therefore, it is interpreted to be a barrier to fluid flow.

The original drive mechanism at King Field was solution gas. There is no consistent oil/water contact in this field because of the heterogeneous nature of the reservoir sands. The original oil in place is calculated to have been about 17 million barrels of which 4.1 million barrels has already been produced. An estimated 1 to 2 million barrels of recoverable reserves may remain for primary and waterflood recovery methods. An improved oil recovery infill drilling program combined with selective waterflooding may be able to recover most of these remaining primary reserves. The data in this report will facilitate the implementation of enhanced oil recovery techniques.

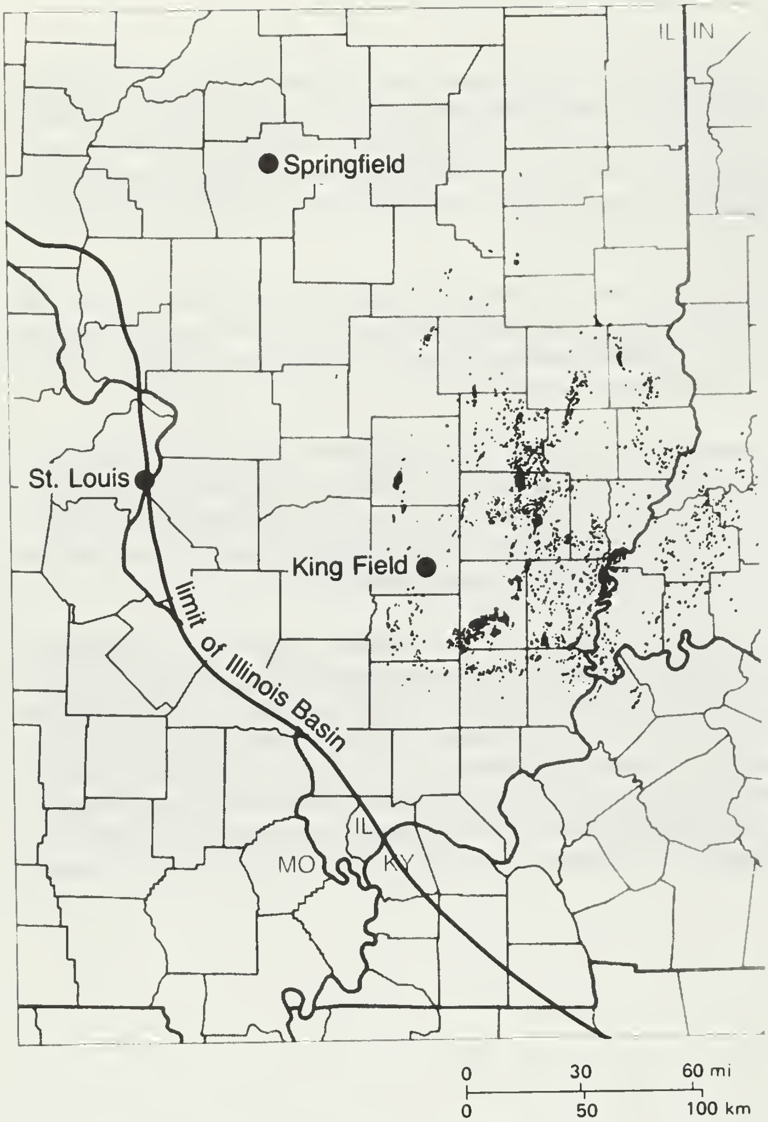


Figure 1 Regional map showing King Field with respect to Aux Vases production within the Illinois Basin (after Howard 1990).

INTRODUCTION

King Field is located 75 miles east-southeast of St. Louis near the western limit of the Aux Vases Formation (Mississippian) producing area (fig. 1). Extending over 1,700 acres in southeastern Jefferson County, the field produces mainly from the Aux Vases (fig. 2) at a depth of about 2,750 feet, although there is minor production from overlying Renault and underlying Ste. Genevieve reservoirs. King Field has produced more than 4.1 million barrels of oil since its discovery in 1942. By 1990, 108 wells had produced oil at King Field.

The goals of this study were to (1) describe the depositional environment and facies architecture of the Aux Vases reservoir at King Field, (2) relate depositional environment to reservoir continuity, (3) estimate remaining mobile oil in place, and (4) delineate areas where improved and enhanced recovery techniques should be applied.

PRODUCTION HISTORY

The Oil Inc., Mace No.1, drilled in 1939, was the first well to test King Field (fig. 3). The well encountered no reservoir facies and was abandoned. The discovery well was drilled 3 years later. This well, the Lewis Production Company, State Game Farm No. 1 (fig. 3), was drilled to a depth of 2,762 feet and was completed open hole for 153 barrels of oil per day (BOPD) and 13 barrels of water per day (BWPD) from the interval 2,740-2,762 feet within the Aux Vases Formation. This well was on the first state-owned land in Illinois to be leased for oil and gas drilling (Folk and Swann 1946).

King Field has undergone three successive periods of development as indicated on a map of well completion dates (fig. 4) and on the decline curve (fig. 5). Event 1 on figure 5a marked the zenith of the first period of development. From 1942 until 1950, 47 wells were drilled with 29 completed as oil wells. In 1943, oil production peaked at more than 36,000 barrels of oil per month. Within 10 years, monthly production declined to less than 10,000 barrels. The second development period began in the mid-1950s when renewed drilling to the Aux Vases reservoir resulted in a total of 71 Aux Vases oil wells and 28 dry holes. Monthly production again climbed above 30,000 barrels (fig. 5b, event 2) and stayed at that level for more than 1.5 years. During this period, production increased across the entire basin (fig. 6, event 2) due to the introduction of the hydraulic fracturing technology. The principal focus for this new technology in Illinois was Aux Vases sandstone reservoirs (Richard Howard, personal communication, ISGS, 1990).

The third period of development at King Field began when Texaco initiated the first waterflood there in 1962 (fig. 5b, event 3). By 1964, there were four active waterfloods in the field. Also, a successful extension in the western part of the field resulted in the completion of an additional eight Aux Vases oil wells. These factors caused a significant increase in production to about 16,000 barrels per month (fig. 5b, event 4). Since 1966, production has steadily declined, and there have been no

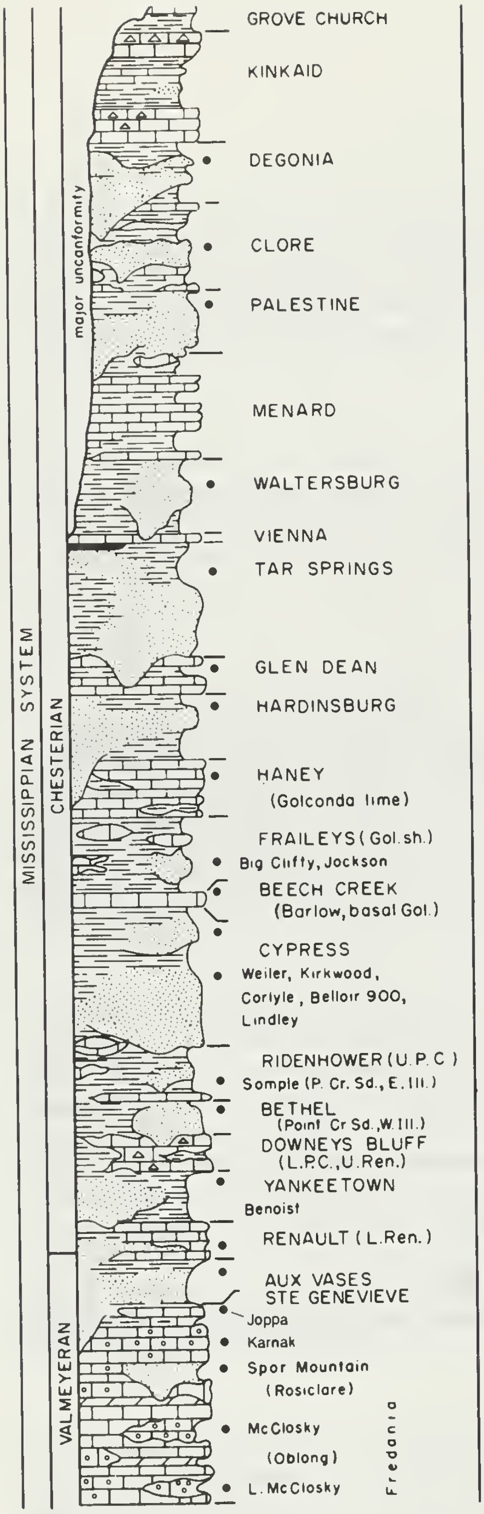


Figure 2 Generalized upper Valmeyeran and Chesterian geologic column of southern Illinois (modified from fig. 3, prepared by David Swann, from Bell et al. 1961).

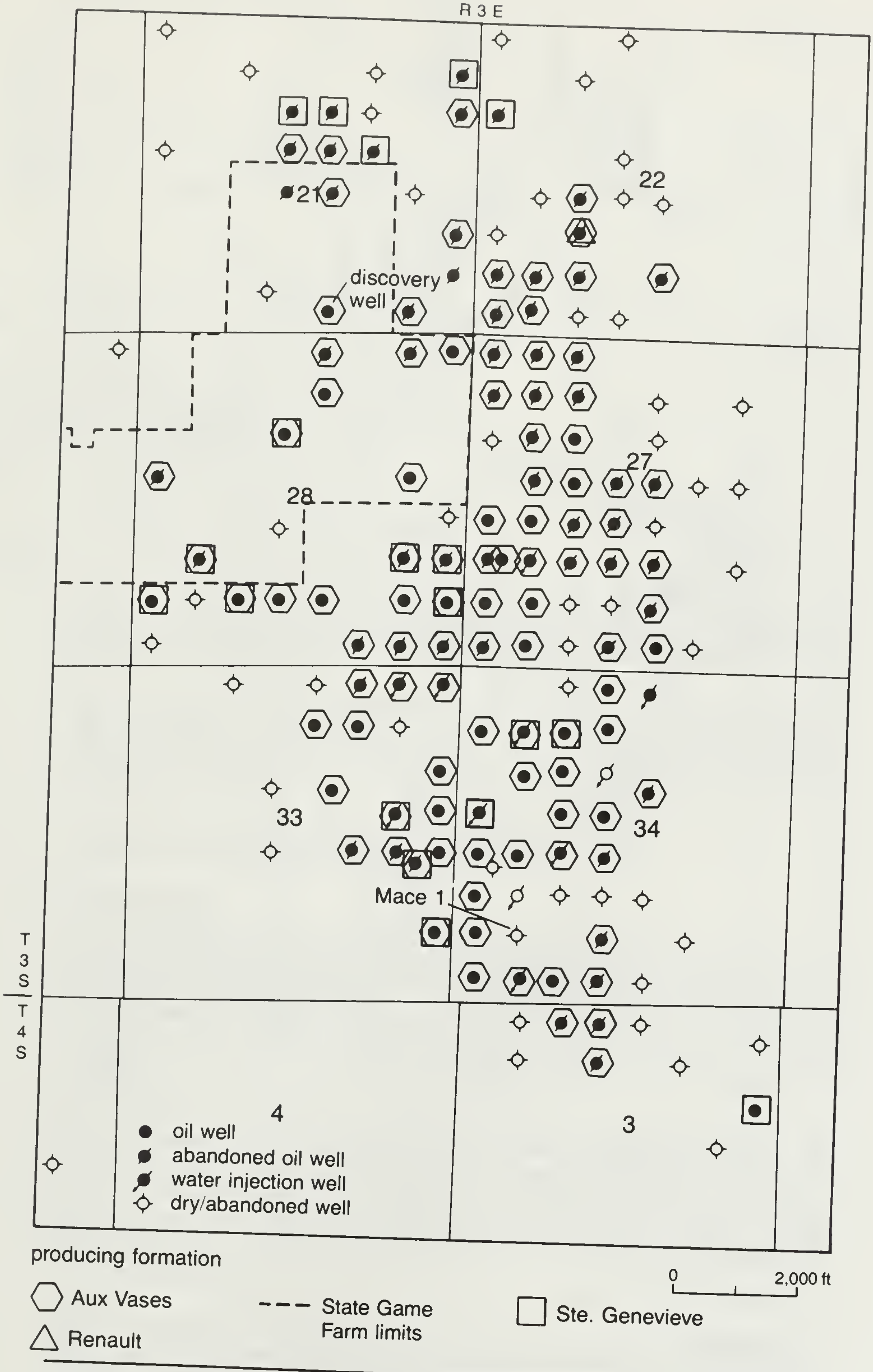


Figure 3 Production map identifying the producing formations in each well.

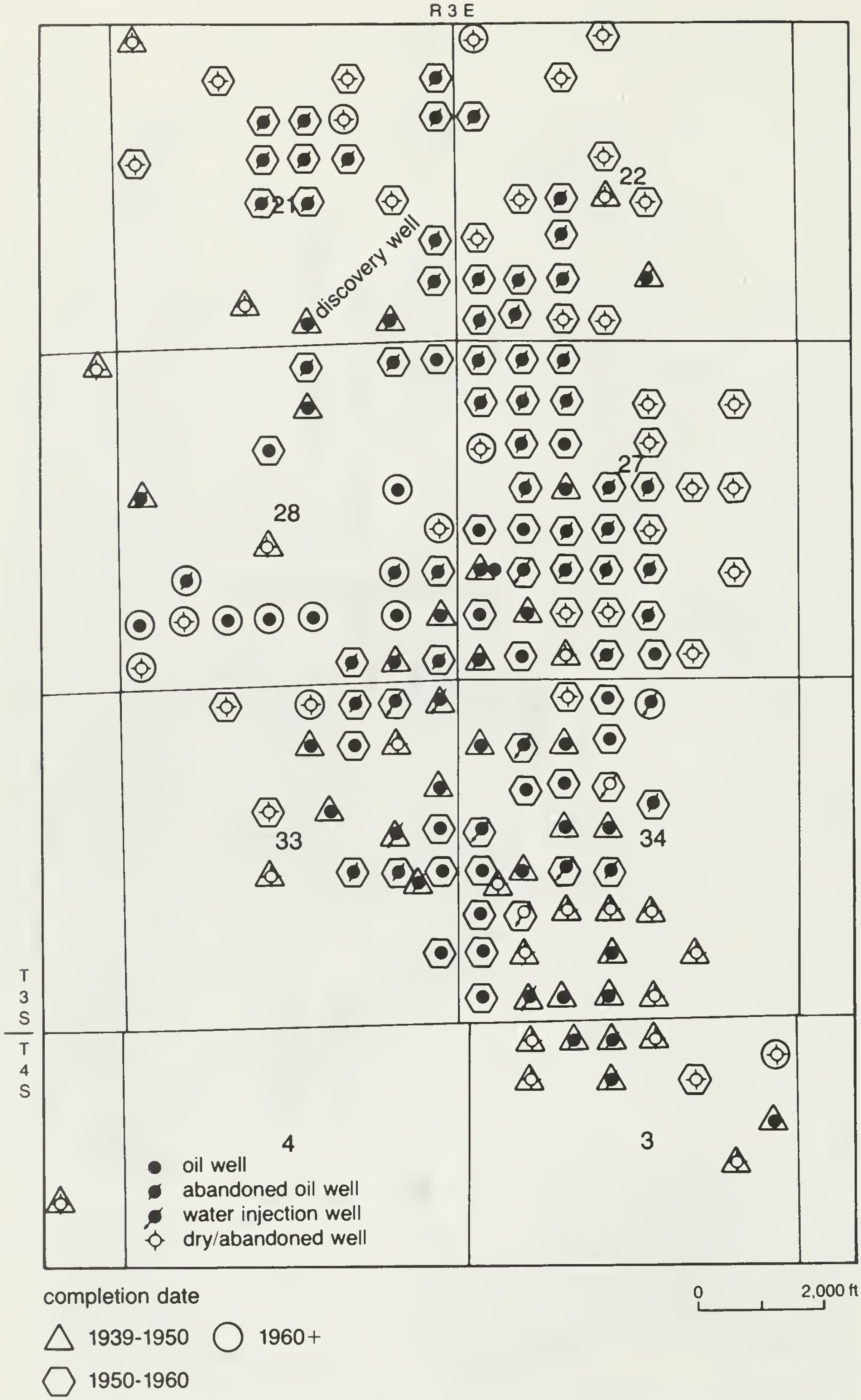


Figure 4 Date-of-completion map for wells at King Field.

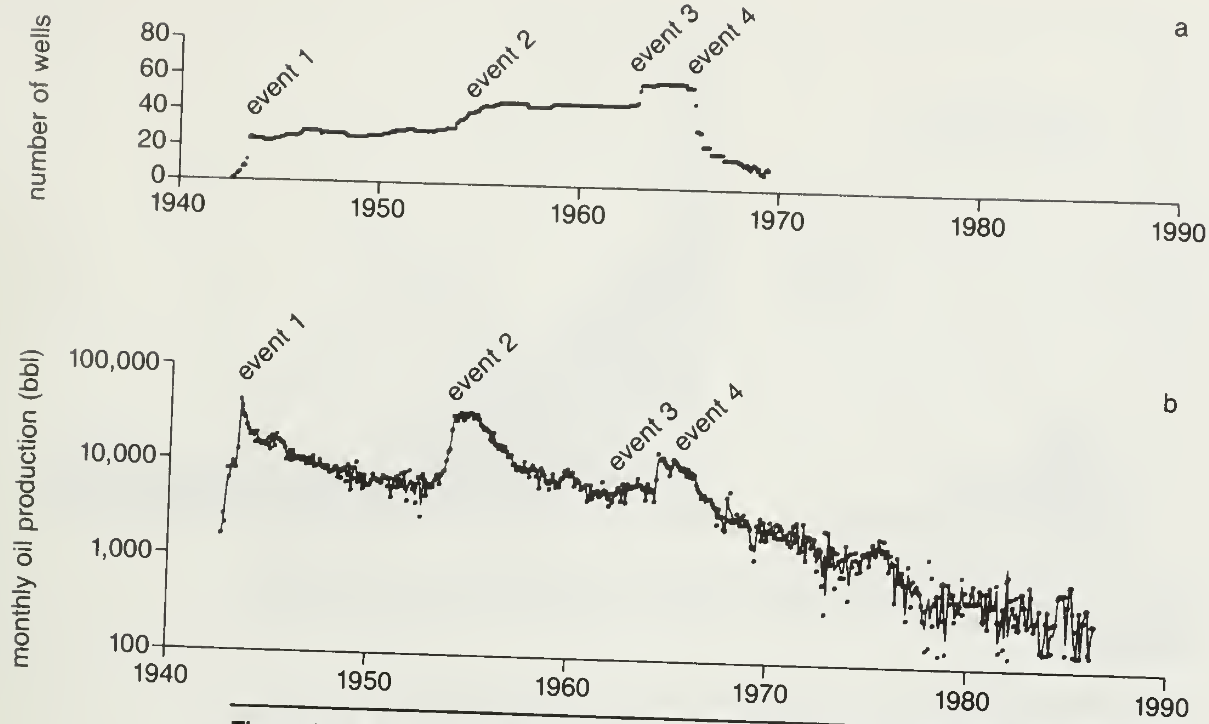


Figure 5 Oil production at King Field. (a) Number of active producing oil wells over time (this number is not available after 1969). (b) Decline curve of total monthly oil production over time.

new waterfloods, outposts, or infill wells. Most of the wells were plugged and abandoned after the collapse of oil prices in 1986. In this period, the field went from five to two active leases. At the time of this report, only four oil wells were still producing.

RESERVOIR FACIES AND GEOMETRY

Stratigraphy

The Aux Vases Formation (fig. 2) is within the uppermost part of the Valmeyeran Series of the Mississippian System. At King Field the Aux Vases Formation is about 50 feet thick and has within it porous and permeable reservoir sandstones that are rarely thicker than 20 feet. These clean, porous reservoir sandstones grade laterally into siltstones, nonporous calcareous sandstones, shales, and limestones. Facies transitions are rapid, commonly occurring within minimum well spacing (660 ft).

Figure 7 is a type log for King Field showing important stratigraphic markers. The Aux Vases is overlain by the carbonate-dominated Renault Formation, a 10-foot-thick brown limestone with negligible porosity. Although the Renault Formation is laterally persistent over most of King Field, the limestones within the formation may be locally absent. The discontinuous nature of these limestones, together with the similarity in resistivity responses of the Renault and Aux Vases limestones, can lead to correlation difficulties.

Carbonate rocks associated with the sandstone have been informally named the "Aux Vases lime." Swann (1963), in his revision of the Valmeyeran and Chesterian classification, assigned the name "Joppa Member of the Ste. Genevieve Limestone" to these carbonate rocks along with the associated sandstones, siltstones, and

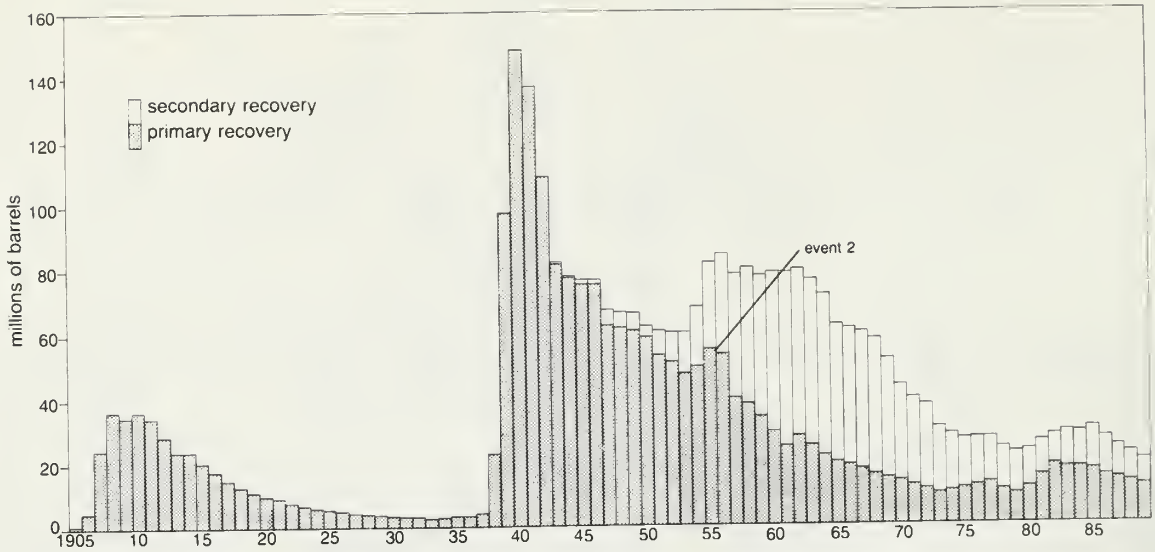


Figure 6 Annual crude oil production for Illinois from 1905 to 1989. Note the increase in production due to fracture treatment of the sandstones beginning in 1954 (from Samson and Bhagwat 1989).

shales that lie between the carbonates and the Karnak Member of the Ste. Genevieve. In this paper, I included rocks of the Joppa Member as part of the discussion of the Aux Vases Formation because I interpret the Joppa as a facies of the Aux Vases.

The Aux Vases is underlain by oolitic limestones of the Karnak Member of the Ste. Genevieve Formation. These oolitic facies have been productive within the field (fig. 3). There is also a small amount of production from the Spar Mountain Sandstone member of the Ste. Genevieve Formation. The Spar Mountain Sandstone has sometimes been incorrectly called the "Rosiclare" by drillers in the basin (Willman et al. 1975).

Structure

Structure maps of the top of the lower limestone in the Renault Formation (fig. 8) and the top of the Karnak Member of the Ste. Genevieve Formation (fig. 9) show an anticline with 40 feet of closure. The Ste. Genevieve structure map is less complex than the Renault structure map because fewer wells have penetrated the Ste. Genevieve horizon. The principal axis of the King Field structure trends north-south. The structure is about 3.5 miles long and 1.5 miles wide. In the shallow Pennsylvanian Shoal Creek Limestone Member, there is 30 feet of closure (Folk and Swann 1946). The crest of the Shoal Creek Limestone is located in sections 33 and 34, whereas the structural crests of the deeper Renault (fig. 8) and Ste. Genevieve Formations (fig. 9) are located in sections 27 and 28. This change in the structural crest locations between the deeper and shallower horizons suggests either (1) a differential compaction due to loading of intervening sandstones and shales or (2) regional tilting of the basin.

Paleogeography

Regional studies of the Aux Vases indicate relatively shallow water deposition across the Illinois Basin (Swann and Bell 1958, Wilson 1985). No evidence indicates any deep water Aux Vases deposition in either the outcrops (Cole 1990) or the subsurface of the Illinois Basin. As discussed later, the Aux Vases Formation at King

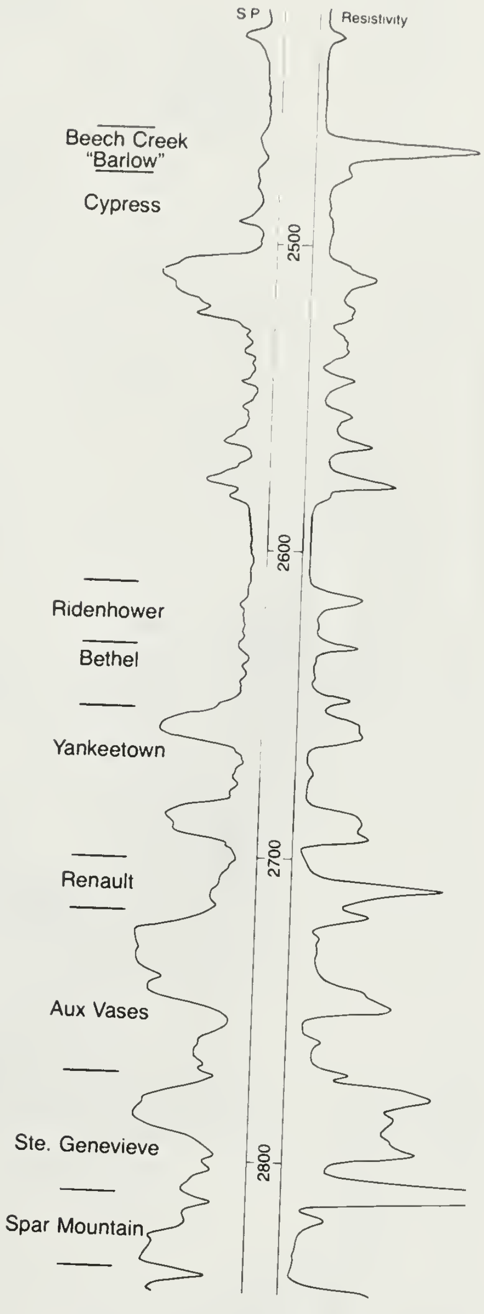


Figure 7 Type log of part of the Valmeyeran and Chesterian section at King Field showing key stratigraphic horizons.

Field is interpreted to have been deposited in a nearshore, mixed carbonate-siliciclastic environment. Generally, the conditions necessary for marine carbonate deposition to occur within a siliciclastic sequence are (1) low input of siliciclastic sediment and (2) an extremely broad tidal zone and corresponding exceptionally wide facies belts that parallel the shoreline, such as occur in epeiric seas (Selley 1978).

Laporte (1967) described the deposition of sediment near mean sea level in an epeiric sea as producing a complex facies mosaic. Minor fluctuations in sea level

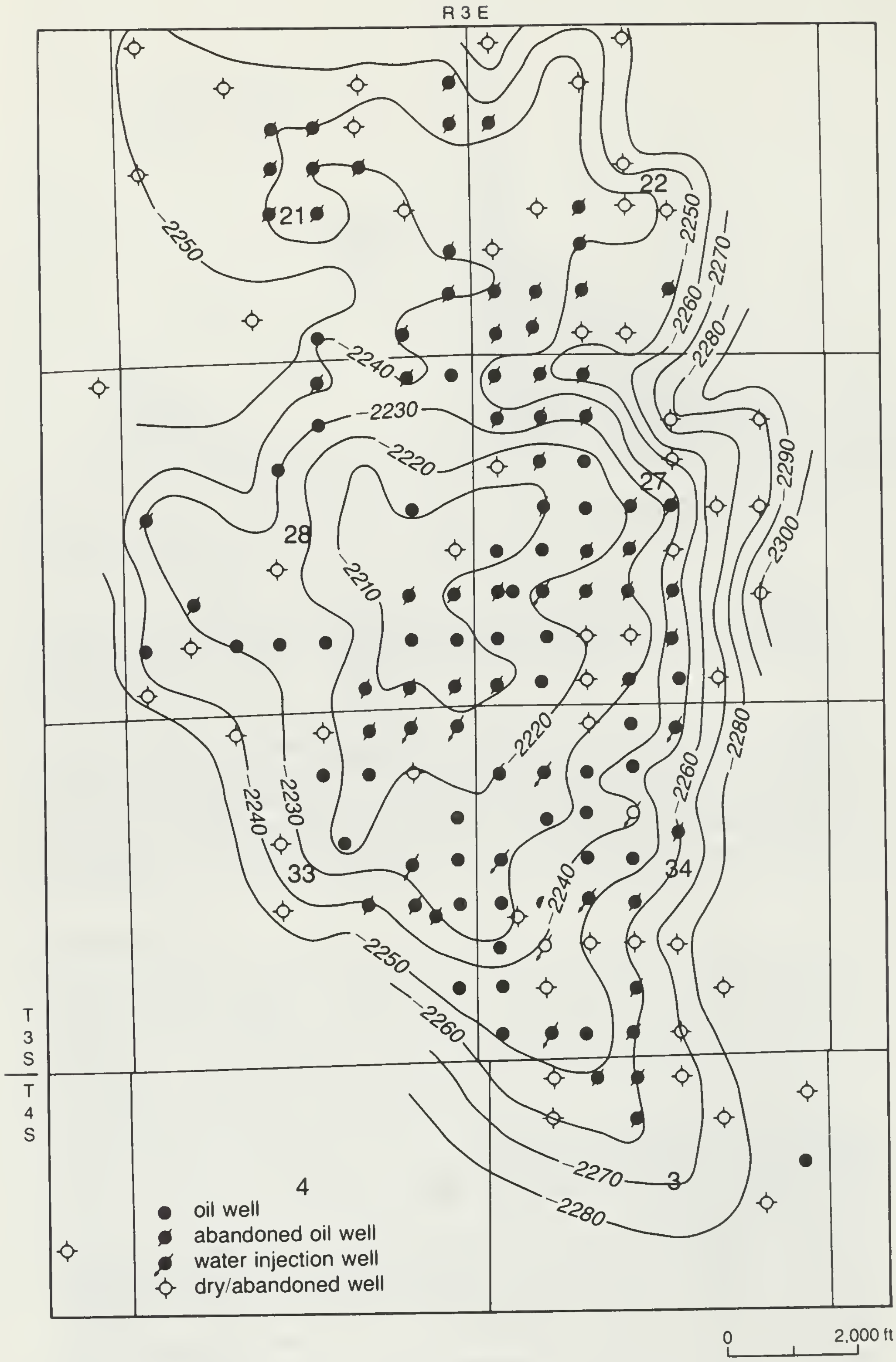


Figure 8 Structure map contoured on top of the Renault Formation (contour interval, 10 ft).

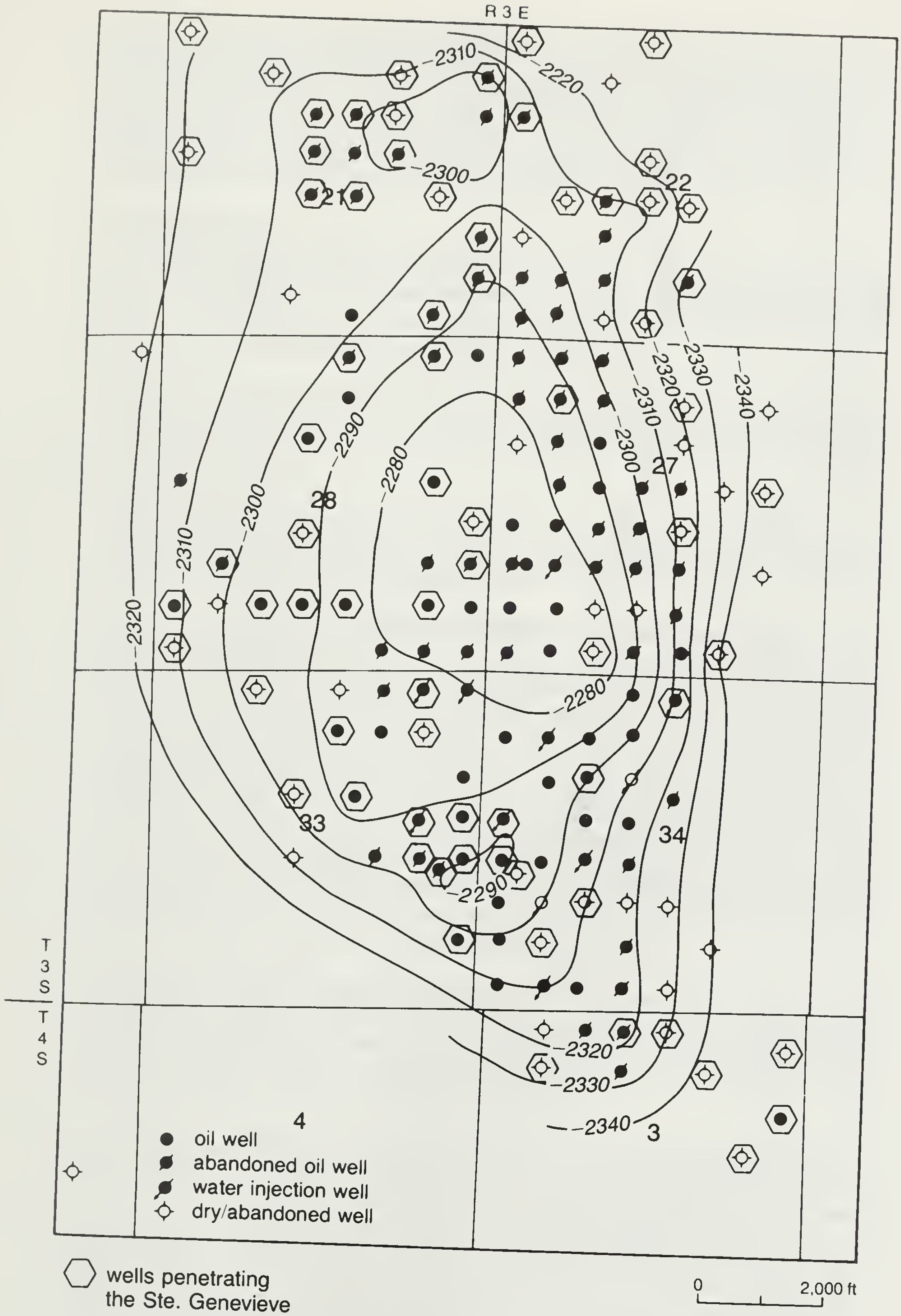


Figure 9 Structure map contoured on top of the Karnak Member of the Ste. Genevieve Formation at King Field (contour interval, 10 ft). Wells that have electric logs through the entire Aux Vases interval are enclosed in a hexagon.

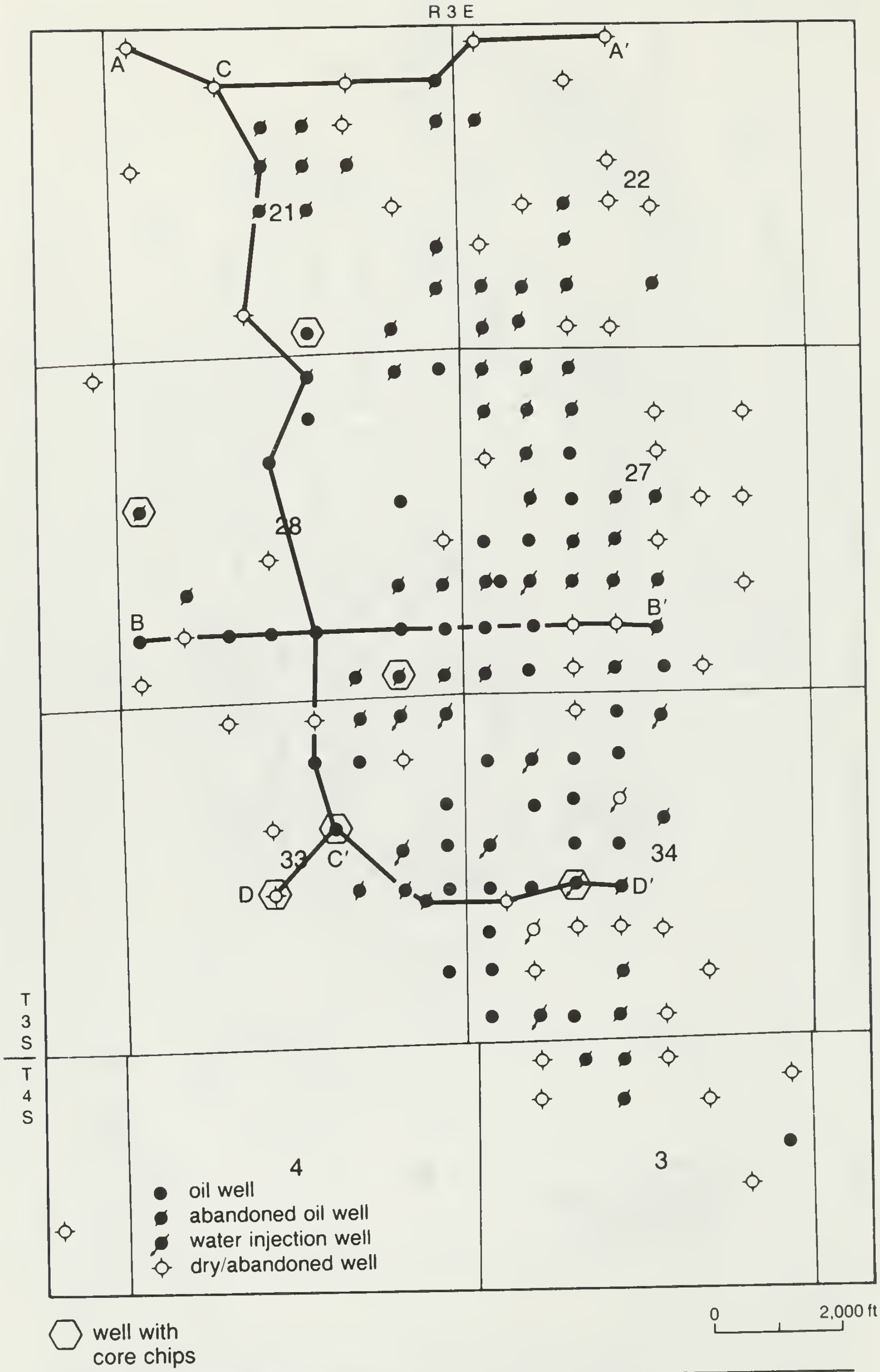


Figure 10 Locations of all wells at King Field for which core chips were available (locations of the four structural cross sections referred to in this report also are shown).

in such a setting can cause rapid changes in depositional environment. Even short-term variations in sea level, such as a strong storm, can have a major influence on the facies patterns in an area (Aigner 1985). A recent epeiric sea analog for the Illinois Basin during Aux Vases time is the Persian Gulf along the Iranian shoreline, where a rapid transition from siliciclastic to carbonate lithofacies (Seibold et al. 1973) resembles the complex facies mosaic described by Laporte (1967).

Petrography

Petrographic analysis of the reservoir facies included study of biscuit-size core chips from six wells (fig. 10). Samples were analyzed using optical petrography, scanning electron microscopy with energy-dispersive X-ray, and X-ray diffraction. No intact whole core was available for study from King Field.

Twenty-one thin sections from the six wells were examined petrographically. All samples were impregnated with a blue-dyed epoxy resin to facilitate identification of porosity. The slides were also stained with Alizarin Red-S to aid in identifying carbonate minerals.

Three principal lithologies are present in the Aux Vases Formation: (1) calcareous lithology, (2) siltstone-shale lithology, and (3) sandstone lithology. As discussed later, each lithology signifies distinct depositional environments.

At least two types of calcareous lithologies are present at King Field: (1) a quartzose-sandy limestone lithofacies and (2) a highly calcareous sandstone lithofacies. The sandy limestone lithofacies is composed of fossil fragments, ooids, and quartz grains with minor feldspar grains (plate 1). Many carbonate grains, as seen in thin section, are heavily abraded. This, together with the presence of ooids, suggests high-energy marine deposition for this facies. The calcareous sandstone lithofacies is composed predominantly of quartz grains, feldspar grains, and local fossil fragments (plate 2). This lithofacies contains some abraded fossil fragments and also is considered to have been deposited in a high-energy environment. Almost all of the pore space in both lithofacies has been occluded by calcite cement. As discussed later, these two lithologies have abundant echinoderm plates, whole and broken, that because of their uniaxial crystal structure, act as sites of precipitation for syntaxial rim cement early in diagenesis (Bathurst 1975).

Laminated green shale to light green siltstone makes up the siltstone-shale lithofacies. The green color of these units may be caused by the relatively large amount of chlorite present in the samples. This lithofacies contains little or no visible porosity or permeability and does not produce commercial quantities of oil or gas. The small grain size indicates relatively low-energy deposition.

The sandstone lithology is characterized by high spontaneous potential, relatively low resistivity, and quartzose fine-grained sand. From visual estimates of thin sections, the best reservoir sand contains more than 80 percent quartz and less than 10 percent feldspar (quartz arenite to subarkose). Various proportions of calcite, quartz, and clay mineral cements are present in most of the sands. The detrital quartz and feldspar grains are very fine grained to medium grained and moderately well sorted. In hand specimen, the best reservoir rock is usually a light brown to light green, fine-grained friable sandstone. Rocks from the poorer producing wells are much less friable and have pore spaces partially occluded with calcite and silica cements.

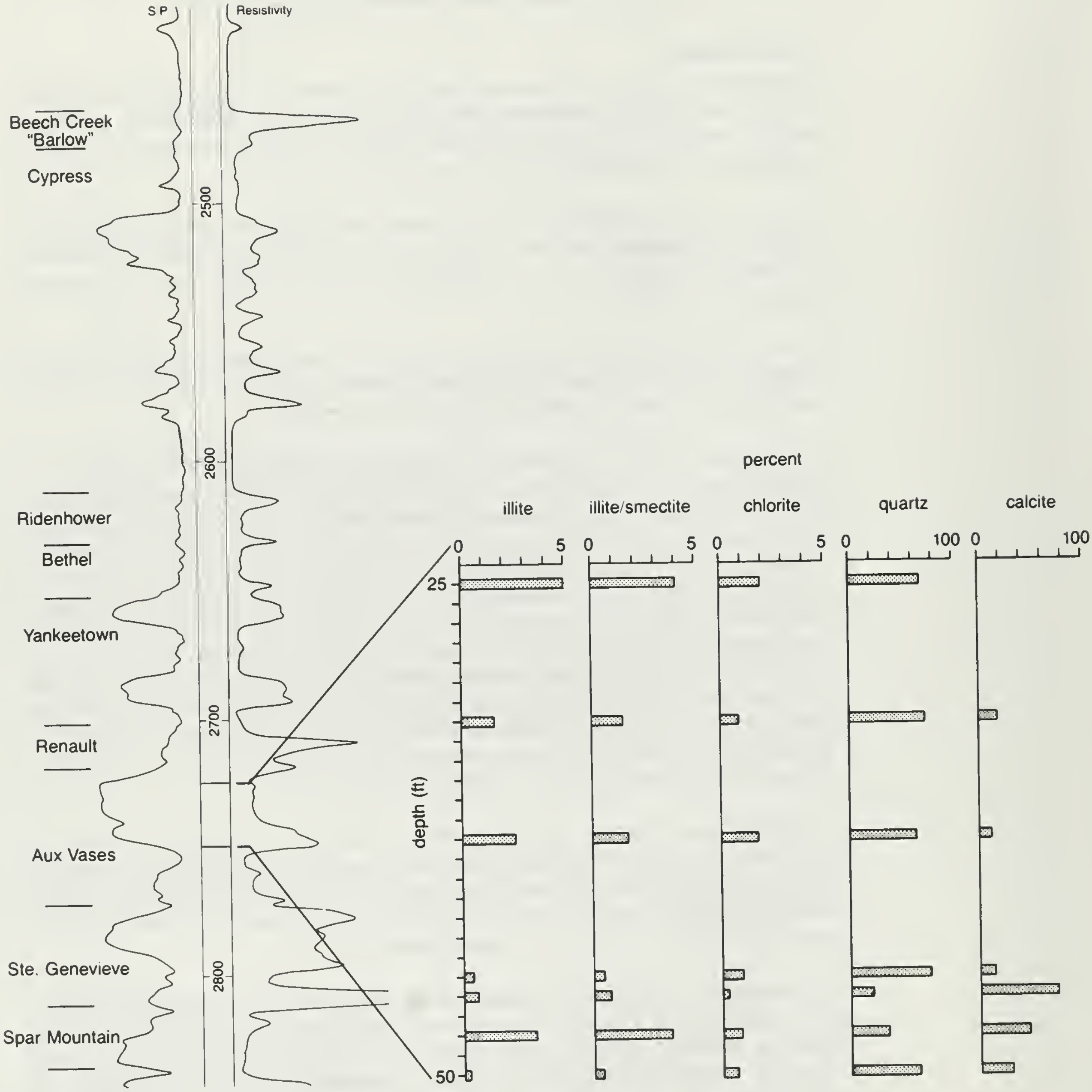


Figure 11 Gulf Ford No.1 electric log and a plot of the variation in mineralogy as measured on the bulk pack by X-ray diffraction analysis. The Aux Vases becomes progressively more calcareous toward the bottom of the cored interval with an associated resistivity increase (location of this well is on fig. 25).

Lithofacies and Depositional Environments

Lithofacies interpreted from electric logs Spontaneous potential (SP) and resistivity curves from old electric logs were used to interpret the lithologies of the Aux Vases Formation. Facies recognition using logs was not totally effective in delineating the areal extent of depositional environments because only 50 percent of the wells penetrated the entire Aux Vases interval (fig. 9).

Resistivity values greater than 40 ohm-m are interpreted as limestones or calcareous sandstones of the calcareous high-energy facies. The Ford No.1 electric log (fig. 11) shows that the zone with the highest percentage of calcite corresponds with the most resistive part of the sandstone. Mineral composition was determined by X-ray diffraction.

Those Aux Vases intervals with an SP that is at least 50 percent of the SP of a clean Cypress sandstone were interpreted as sandstones, whereas those with less than 50 percent of the SP of a Cypress sandstone were interpreted as shaly sandstones or siltstones. The shale baseline is delineated by shales directly above the Aux Vases. A relatively thick, clean Cypress sandstone has a consistent log character and is therefore a good unit with which to standardize the SP for making comparisons between wells (Leetaru 1990). Additionally, analyses of numerous cores in a four-county area reveal that porosity values for clean Cypress sandstones do not vary by large amounts (Leetaru 1990).

Depositional facies The different lithologies of the Aux Vases at King Field signify depositional environments, which are discussed below.

Calcareous offshore high-energy facies The calcareous facies are interpreted to have been deposited in an offshore high-energy environment. This facies is characterized by log intervals with measured resistivities greater than 40 ohm-m. In this study, both the fossiliferous limestone and the calcareous sandstone are included in the calcareous offshore high-energy facies because they cannot be differentiated using the electric logs and there are not enough data from cores and samples to do so by visual inspection.

Figure 12 is a map of the percentage of calcareous offshore high-energy facies in the total Aux Vases interval. Most of the wells at King Field penetrated some of this offshore high-energy facies. In some areas, such as the southern part of the field, 40 percent of the Aux Vases thickness consists of this facies. The southern part of King Field (sections 33 and 34) produces from this facies, but production is only marginally commercial. This minor development of porosity in the calcareous offshore high-energy facies may have occurred because of a slight change in depositional or diagenetic environment, but not enough data are available to be definitive. Elsewhere, carbonates act as permeability barriers and increase reservoir compartmentalization.

Offshore low-energy and tidal flat facies On the basis of its fine grain size, the siltstone-shale lithofacies is interpreted to have been deposited in both an offshore low-energy and a tidal flat environment. This facies can form lateral and vertical permeability barriers that increase reservoir heterogeneity. The siltstones and shales of the facies are characterized by a relatively low SP response. The unit most easily correlated on electric logs in the Aux Vases at King Field is the lower siltstone layer overlying the carbonate facies of the Ste. Genevieve Formation (fig. 13). Unlike other siltstones that occur higher in the Aux Vases, the lower siltstone is relatively

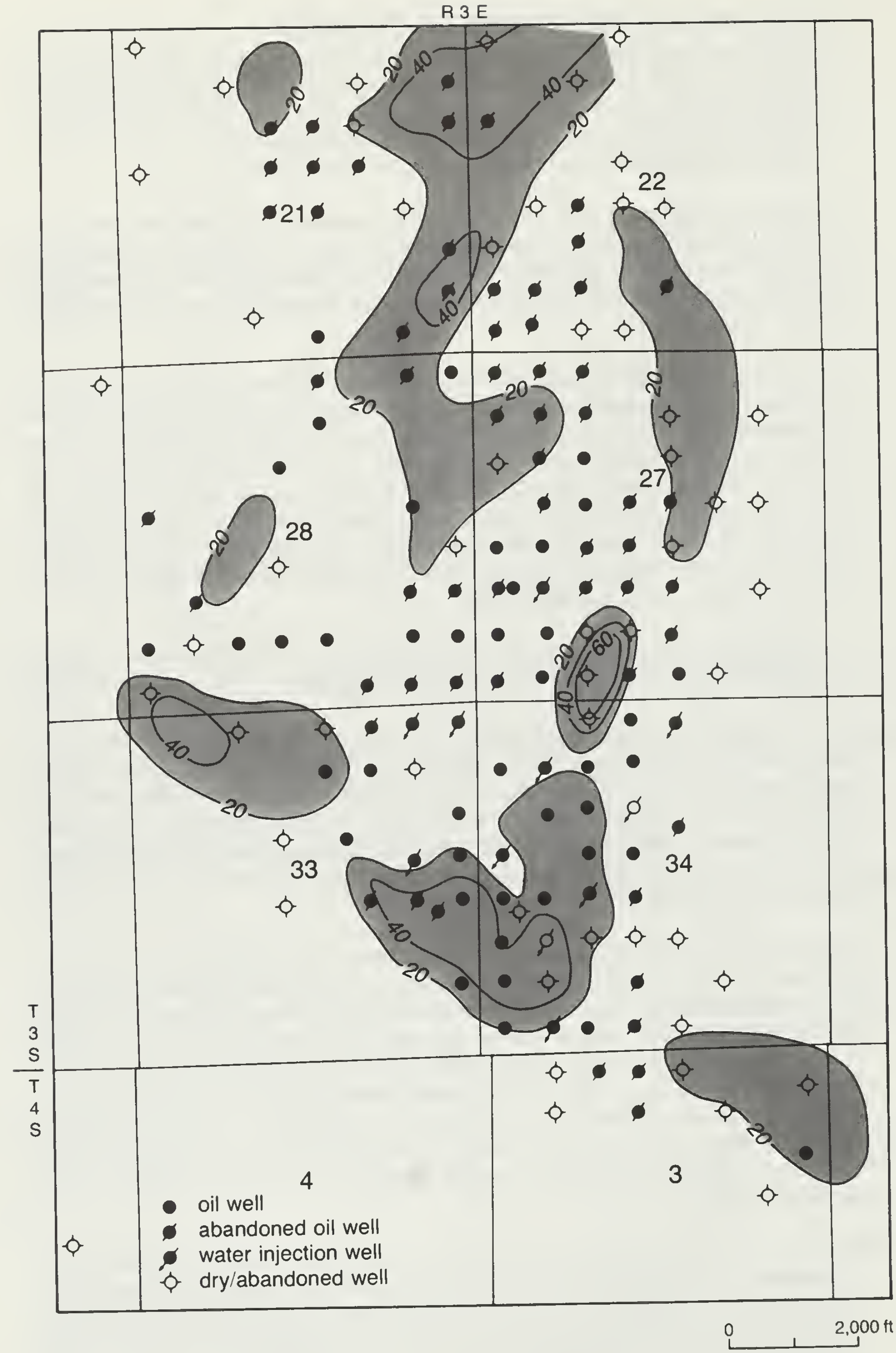


Figure 12 Percentage of the Aux Vases Formation containing calcareous high-energy facies. Areas with greater than 20 percent limestone are highlighted.

continuous across most of the field, suggesting deposition in slightly deeper water (possibly below wave base). In places, this lower siltstone apparently grades laterally into the calcareous offshore high-energy depositional facies as seen as in cross section *B-B′*, fig. 14).

The tidal flat siltstone-shale intervals higher in the Aux Vases generally are not laterally continuous and give way laterally to sandstone intervals. The inability to correlate shale markers for more than 1,300 feet suggests a more tidal-dominated nearshore environment (Weber 1982). The reason for this lack of shale continuity is the presence of channels that bifurcate the tidal flat environment. In cross section *C-C′* (fig. 15), for example, the siltstone in well 2313 is erosionally truncated in well 2317 by a 30-foot-thick sandstone unit. I interpret this thick sandstone unit to be a remnant of a tidal channel and the discontinuous siltstones to be part of the tidal flat facies.

Tidal channel and offshore bar sandstone facies The clean sandstone facies, which is defined by an SP that is at least 50 percent of the SP of a clean Cypress sandstone, is interpreted as either a tidal channel or offshore bar deposit. The north-south trending sand bodies (*x-x′* and *y-y′*, fig. 16) are interpreted to be part of a tidal channel sequence. The sand body delineated by line *x-x′* (fig. 16) apparently continues for a couple of miles in a northwesterly direction away from the study area (Wafer 1955). This linear geometry suggests that the *x-x′* sand body is a channel. Cross section *C-C′* (fig. 15) passes along the axis of this north-south trending sand body. Except for well 488, the Aux Vases sandstones on cross section *C-C′* all have apparent upward-fining or blocky patterns on the SP. Both the upward-fining and the blocky SP shapes are suggestive of channel sands.

Although the reservoir sands within the channel are stratigraphically equivalent, production data indicate that they are not in communication. For instance, well 2317 tested at 30 BOPD, whereas the two adjoining wells, which are structurally equivalent, did not produce any hydrocarbons. This lack of production in the adjoining wells may have been caused by either compartmentalization of the reservoir sand or faulty evaluation of the wells. I believe that the sands are not in communication; this is a common example of reservoir heterogeneity at King Field.

The thick sand present in the western part of cross section *B-B′* (fig. 14) appears to be wet to the east (note abandoned wells 1334 and 2358). Another oil-saturated reservoir, in well 2351, apparently not in communication with the rest of the reservoir, can be found downdip from these two abandoned tests to the east. This well had an initial production of 270 BOPD from the Aux Vases sand.

Many of the wells along the axis *z-z′* (fig. 16) have an apparent coarsening-upward SP pattern, which suggests an offshore bar deposit. The axis of the postulated offshore bar strikes parallel to the postulated paleoshoreline. This is consistent with the hypothesis of Potter (1962) and Swann and Bell (1958), who said that the primary influx of Aux Vases terrigenous sediment came from the north to northwest.

Some of the most productive wells in the field are located in the offshore bar facies, for two reasons: (1) the best reservoir rock in an offshore bar is near the top of the sand unit where sands are coarser, and (2) the offshore bars are located near the structural crest of King Field.

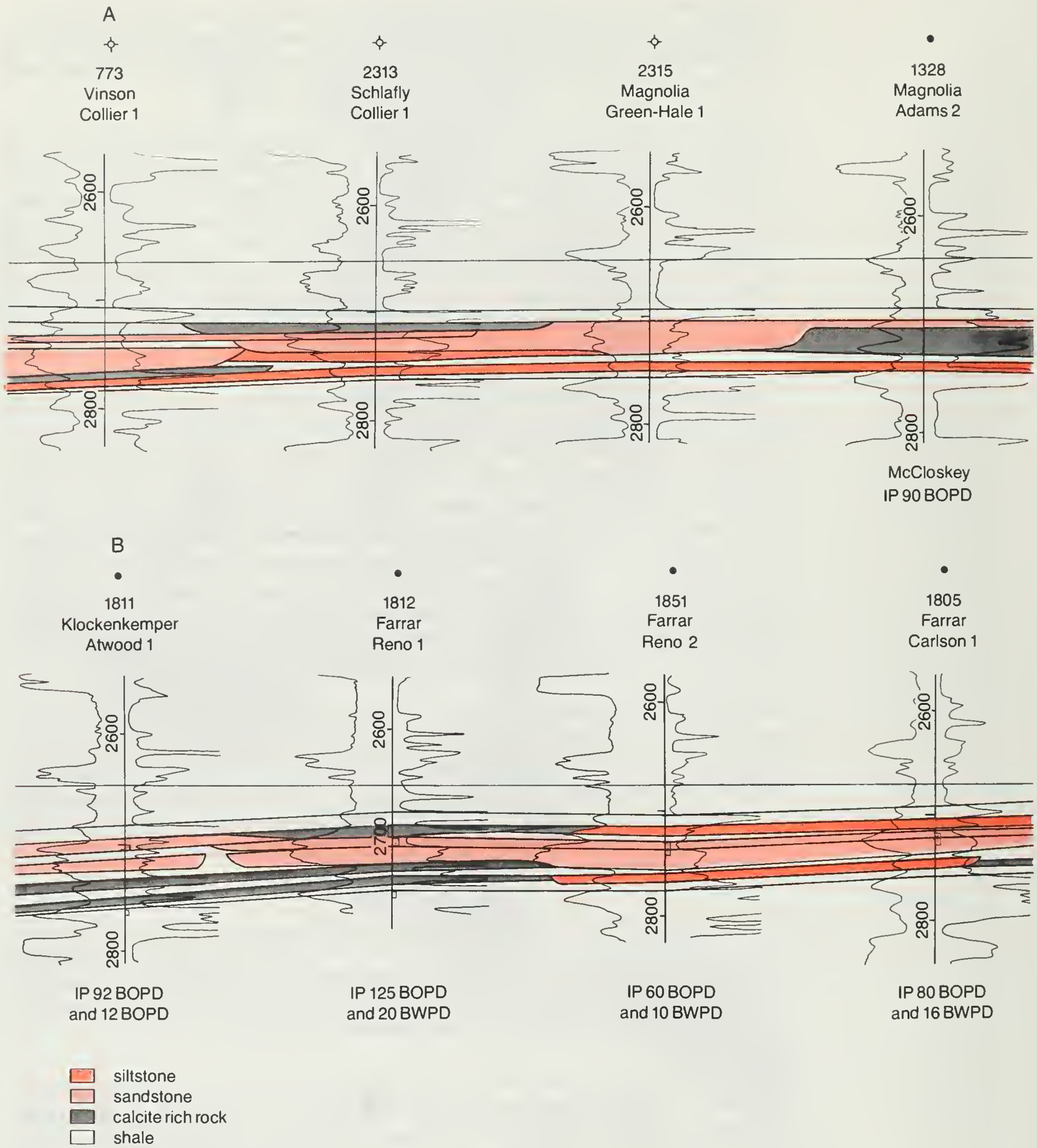


Figure 14 Cross section *B-B′*. Note that oil-producing wells can be found structurally downdip from dry holes (location of this cross section is shown on fig. 10).

Carbonate and clastic lithofacies interrelationships The mixture of carbonate and siliciclastic lithofacies at King Field was probably caused by temporal fluctuations in the supply of siliciclastic sediment coupled with the presence of an extremely broad tidal zone. A decrease in the input of siliciclastic sediment could give the appearance of a relative rise in sea level, when base level is raised and marine

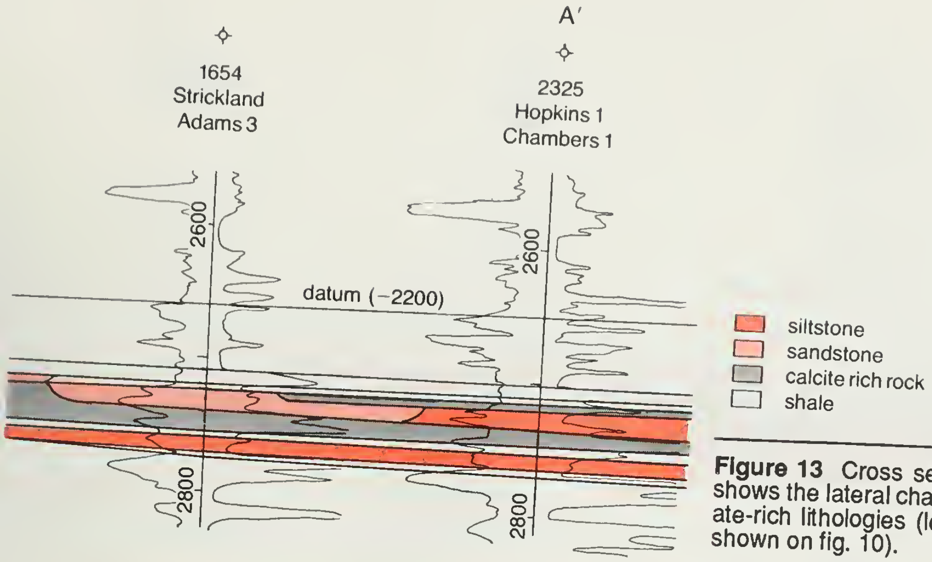
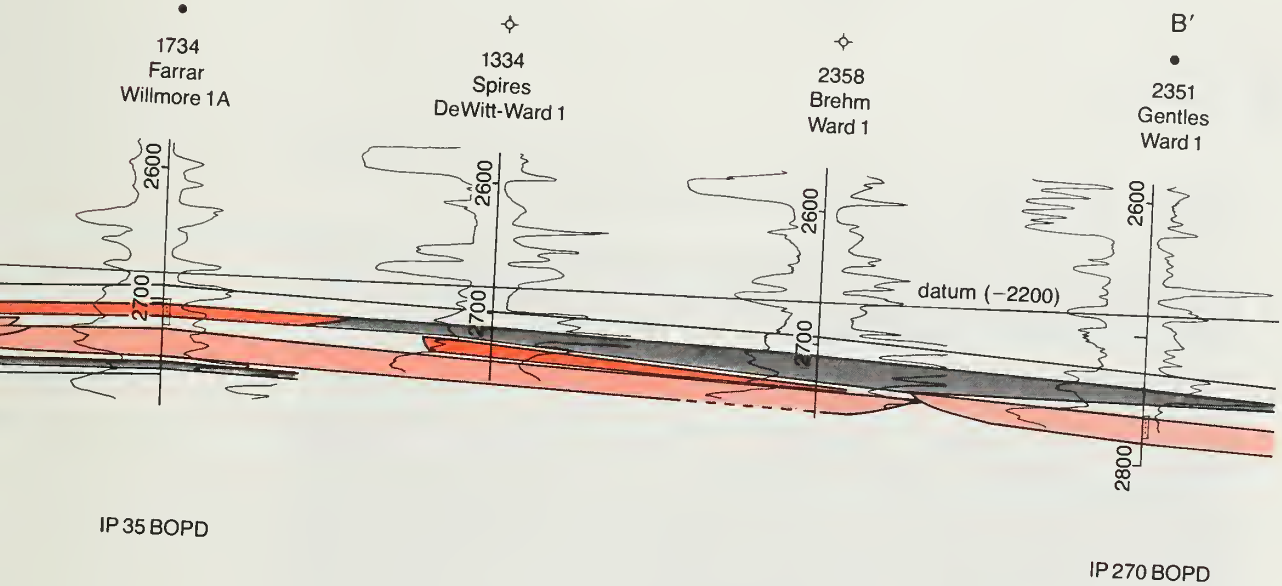


Figure 13 Cross section *A-A′*. This cross section shows the lateral change from siliciclastic to carbonate-rich lithologies (location of this cross section is shown on fig. 10).



sedimentation prevails. Also, lateral shifting of the fluvial system (or depocenter) can cause significant changes in sediment influx resulting in many lateral and vertical transitions between siliciclastic and carbonate lithofacies. A modern analog for this vertical transition is the North Puerto Rico Shelf (Pilkey et al. 1988), where the shifting of the distributary mouth changes the depocenter of the siliciclastic sediment. The siliciclastics are then overlain by carbonate sediment.

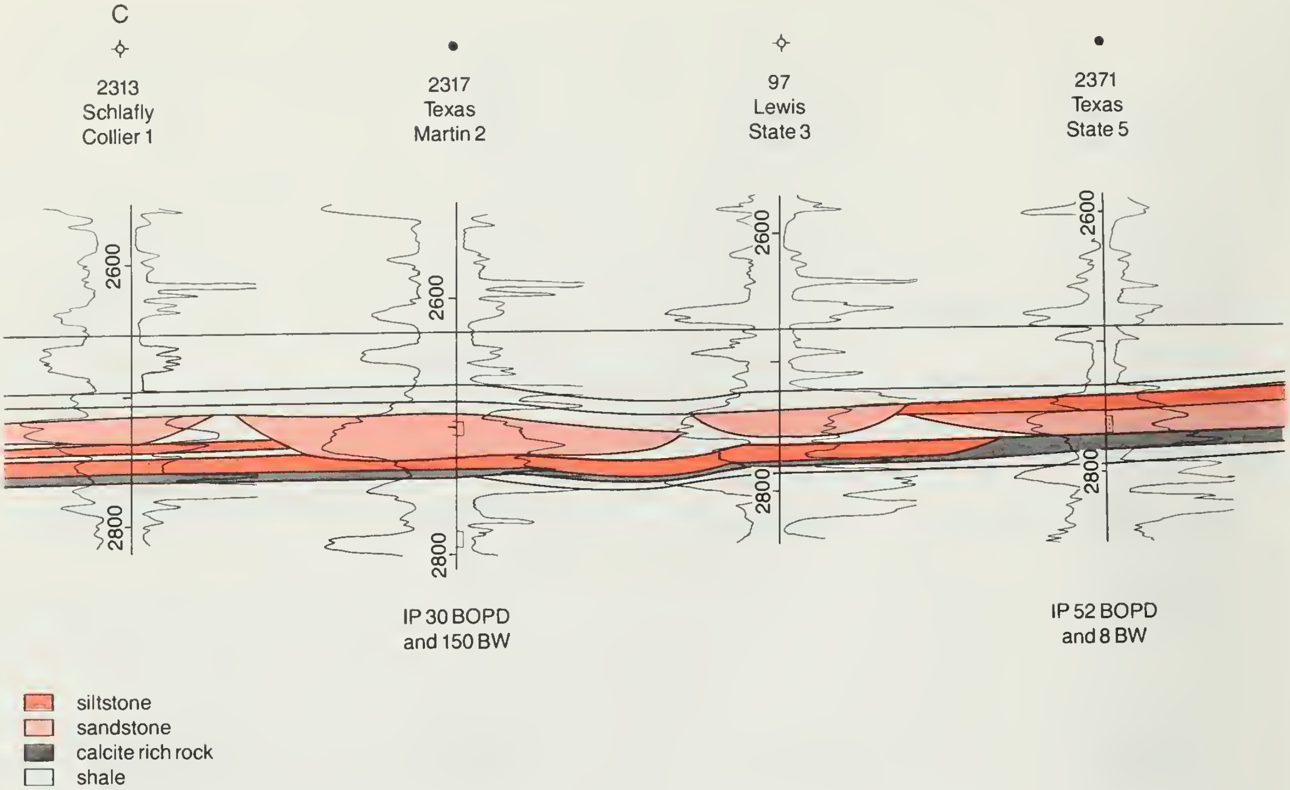
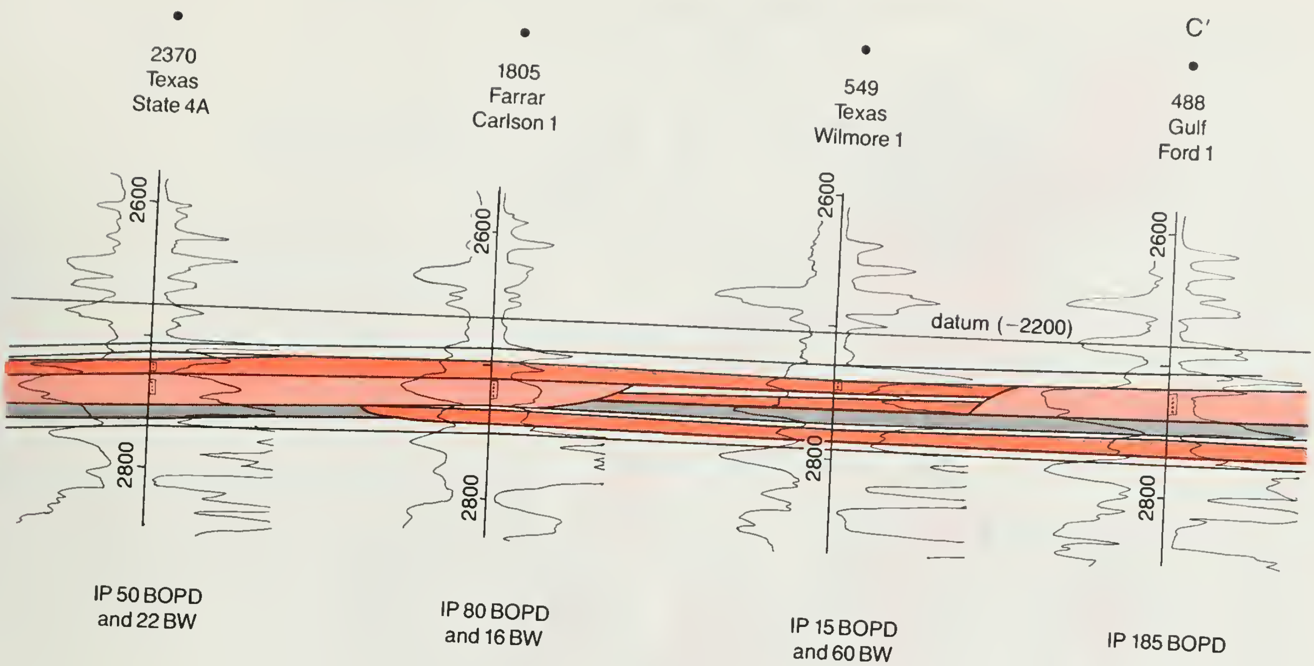


Figure 15 Cross section *C-C'*. This section is along the axis of one of the principal Aux Vases sand bodies (location of this cross section is shown on fig. 10).

An isopach map constructed for the interval from the top of the Renault Limestone to the top of the Karnak Member of the Ste. Genevieve Formation (fig. 17) shows a pattern of thickening and thinning that is inversely similar to the pattern on the map of the percentage of calcareous offshore high-energy facies in the Aux Vases (fig. 12). Although differential compaction of the Aux Vases may be responsible for some anomalies, this isopach map (fig. 17) may represent paleotopography during deposition. I interpret the areas of thinner Aux Vases-Renault to generally represent paleotopographic highs. In these areas, the calcareous facies (fig. 12) is relatively thick and the sandstone facies (fig. 16) is relatively thin, suggesting topographic control of tidal channels. The correlation between the thick and thin intervals on the net clean sand isopach (fig. 16) and the Renault Limestone-Ste. Genevieve isopach (fig. 17) might have been even stronger, except that differential compaction caused by discontinuous beds of shales and sandstones within the Aux Vases probably has distorted overlying beds.

Sediments deposited in offshore environments commonly are widespread (Weber 1982), yet, at King Field, the calcareous offshore high-energy facies apparently is restricted (fig. 12). This limited distribution suggests that the calcareous offshore high-energy facies is truncated by channels interpreted to be of tidal origin and composed of Aux Vases sandstones. Cross section *A-A'* (fig. 13), the northernmost section, is constructed in an east-west direction roughly perpendicular to the structural and stratigraphic strike of the field. None of the wells along this cross section produce from the Aux Vases sandstone facies because the reservoir there is structurally low and contains water. The calcareous offshore high-energy facies on this cross section is represented by the highly resistive Aux Vases log character



in well 1328. The sandstone intervals in wells 2313, 2315, and 773 represent a channel system that apparently scoured into the calcareous offshore high-energy facies. This calcareous offshore high-energy facies is still common in the eastern part of this cross section (fig. 13).

A model of the relationship between the clastic and calcareous lithologies is illustrated in figure 18. The Aux Vases at King Field was deposited in a mixed carbonate-clastic nearshore shallow marine environment. The calcareous lithofacies represents remnants of the offshore high-energy facies left after scouring by tidal channel processes. Tidal channel sandstone sequences would include not only the channel deposits but also point bar deposits. (Note that this illustration is just one slice in time and is hypothetical; actual facies patterns present at King Field are much more complex than shown in the diagram.)

Influence of Depositional Environment on Production

A comparison of the Aux Vases net sand isopach map (fig. 16) and the map of the reported initial production from scout tickets (fig. 19) substantiates the strong relationship between the distribution of clean (50% SP) sand and the highest initial production tests. This strong relationship is apparent, even though the initial production as reported by the operator is not always accurate due to factors such as choke size, pumping equipment, and duration of the test. The contour interval on the initial production map is 50 BOPD with a suggested economic cutoff and lowest contour of 10 BOPD. In this study, wells with an initial production of less than 10 BOPD were considered noncommercial.

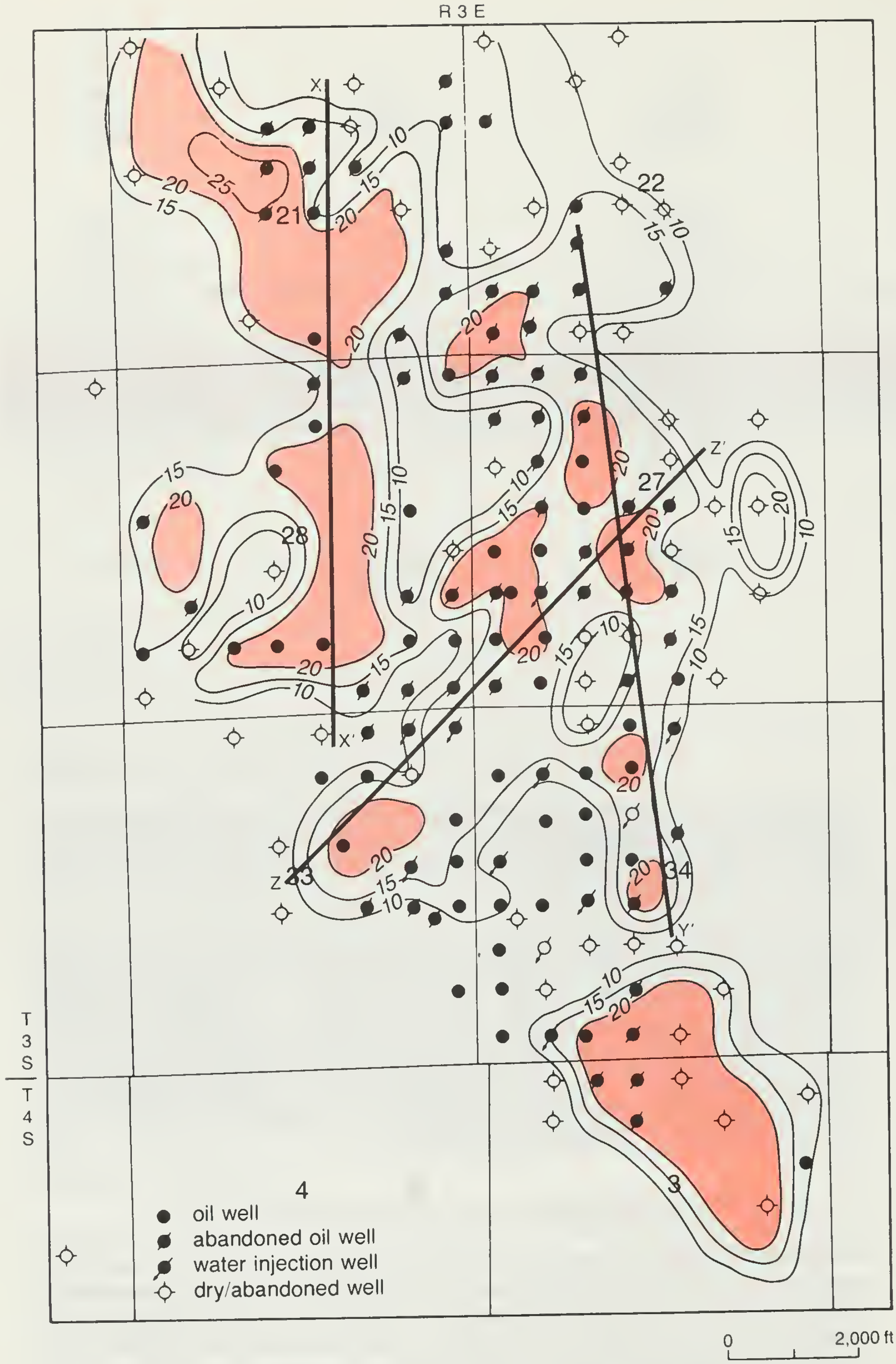


Figure 16 Net thickness (ft) of clean Aux Vases sand (contour interval, 5 ft). A clean sandstone is defined as having an SP response that is at least 50 percent of the SP response of clean, thick Cypress sandstone. This map also shows the axis of the more significant sand units (*x-x′*, *y-y′*, and *z-z′*). Areas with more than 20 feet of sand are highlighted.

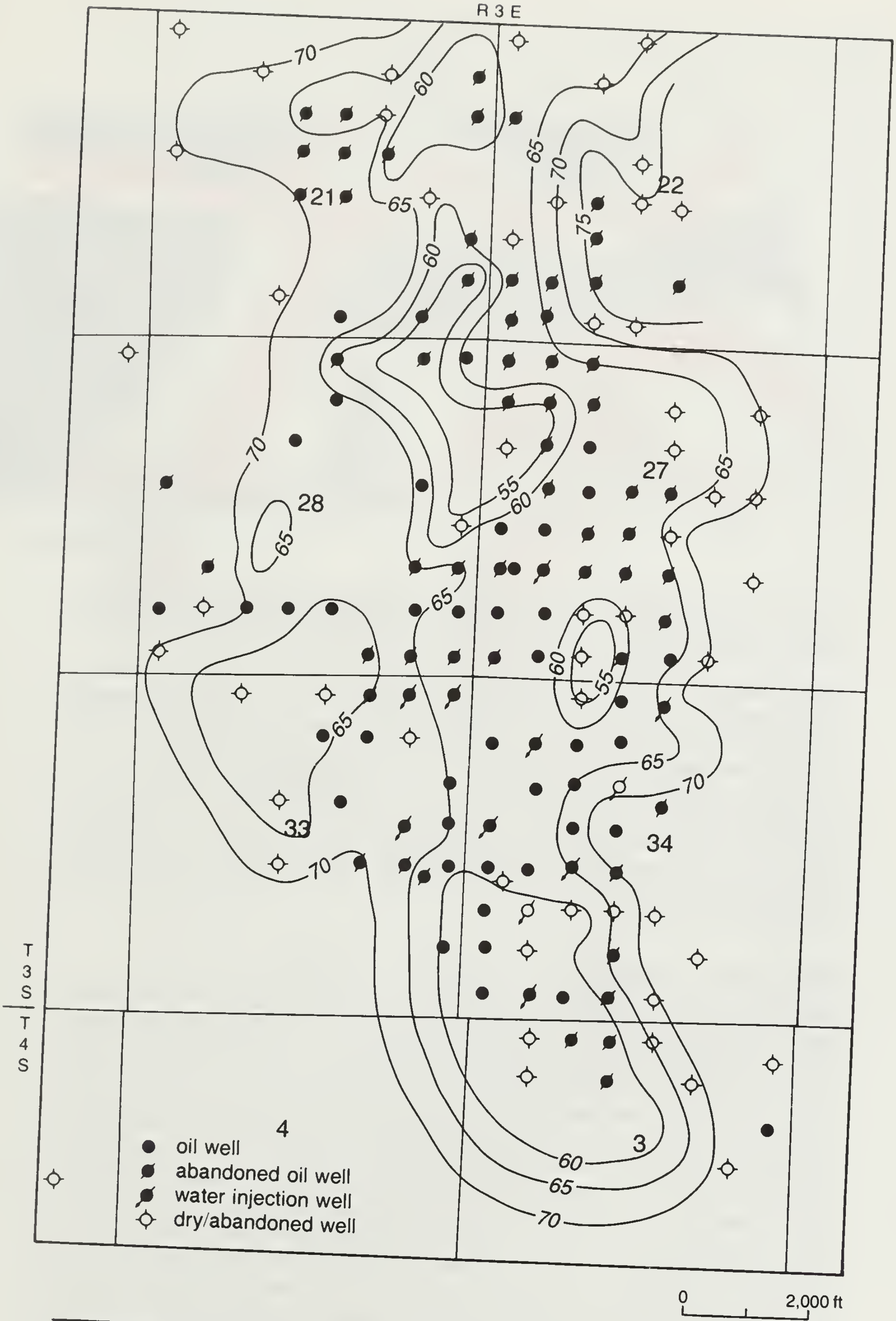


Figure 17 Isopach map of top of the Renault Formation to top of the Karnak Member of the Ste. Genevieve Formation (contour interval, 5 ft). Map represents the approximate paleotopography during deposition of the Aux Vases Formation.

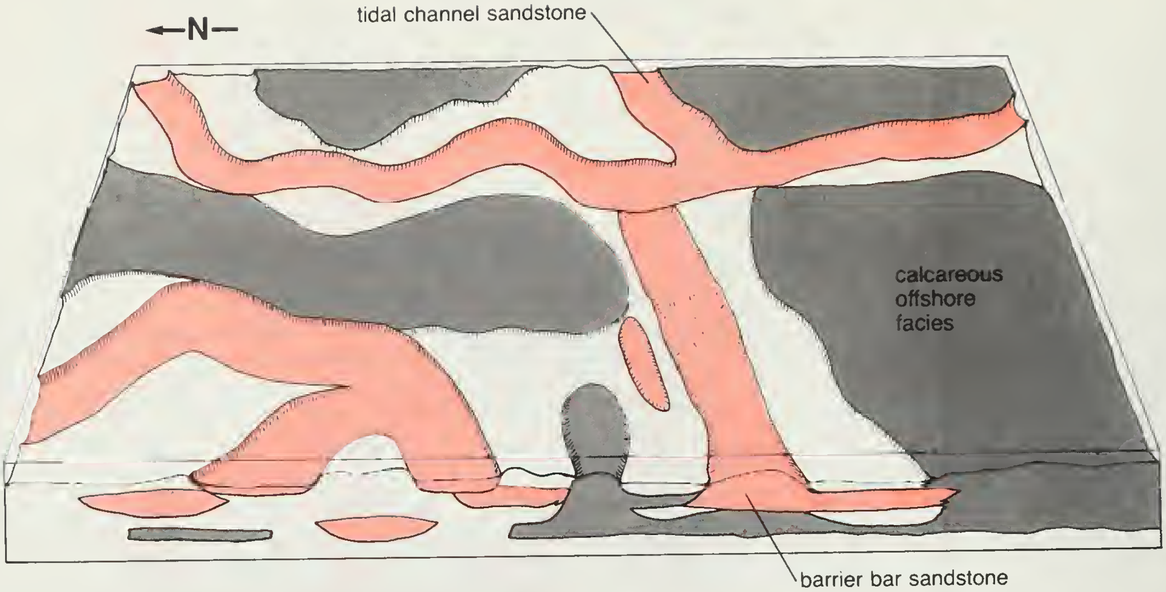


Figure 18 Block diagram illustrating the hypothetical depositional environment that existed when the sandstone facies of the Aux Vases was deposited at King Field.

The deposition of the Aux Vases in a mixed carbonate-siliciclastic nearshore shallow marine environment resulted in a heterogeneous reservoir at King Field composed of an intercalated sequence of sandstones, siltstones, shales, and carbonates. This heterogeneity resulted in compartmentalization of the reservoir, making a delineation of the true limits of the field difficult. Dry and abandoned wells do not necessarily signify the limits of the Aux Vases reservoir at King Field. Indeed, good oil production is possible downdip from wet sands (fig. 14). This reservoir heterogeneity has a significant impact on the ideal well spacing for primary and especially secondary recovery. As discussed later, 10-acre well spacing may not be adequate for effective oil recovery.

Diagenesis and Its Effect on Reservoir Quality

Cement The Aux Vases reservoir sandstones at King Field contain three types of cement: quartz, clay, and calcite. Most samples contain all three types of cement. Silica cement in the form of quartz overgrowths is one of the principal agents in occluding primary porosity. Porosity rapidly decreases with an increase in quartz cement because, unlike clay minerals, quartz grains do not contain micropores. Continuous clay mineral coatings seem to inhibit the formation of quartz cement (Pittman and Lumsden 1968, Thomson 1982). The best Aux Vases reservoir rock has a thin relatively continuous dusting of clay mineral around each quartz grain. Only at the grain-to-grain contact is the clay coating missing (fig. 20). Clay mineral coatings are more discontinuous in the less porous part of the Aux Vases and calcite and quartz cement are more abundant. The clays were identified from X-ray diffraction and constitute less than 10 percent of bulk volume (see detailed analysis of clay mineralogy in appendix B). These clays occur as various proportions of illite, mixed-layered illite-smectite, and chlorite. Preliminary results from X-ray diffraction indicate that a large percentage of the authigenic clay in the more porous rocks is a type of iron-rich chlorite (Moore and Hughes 1990). However, analyses by

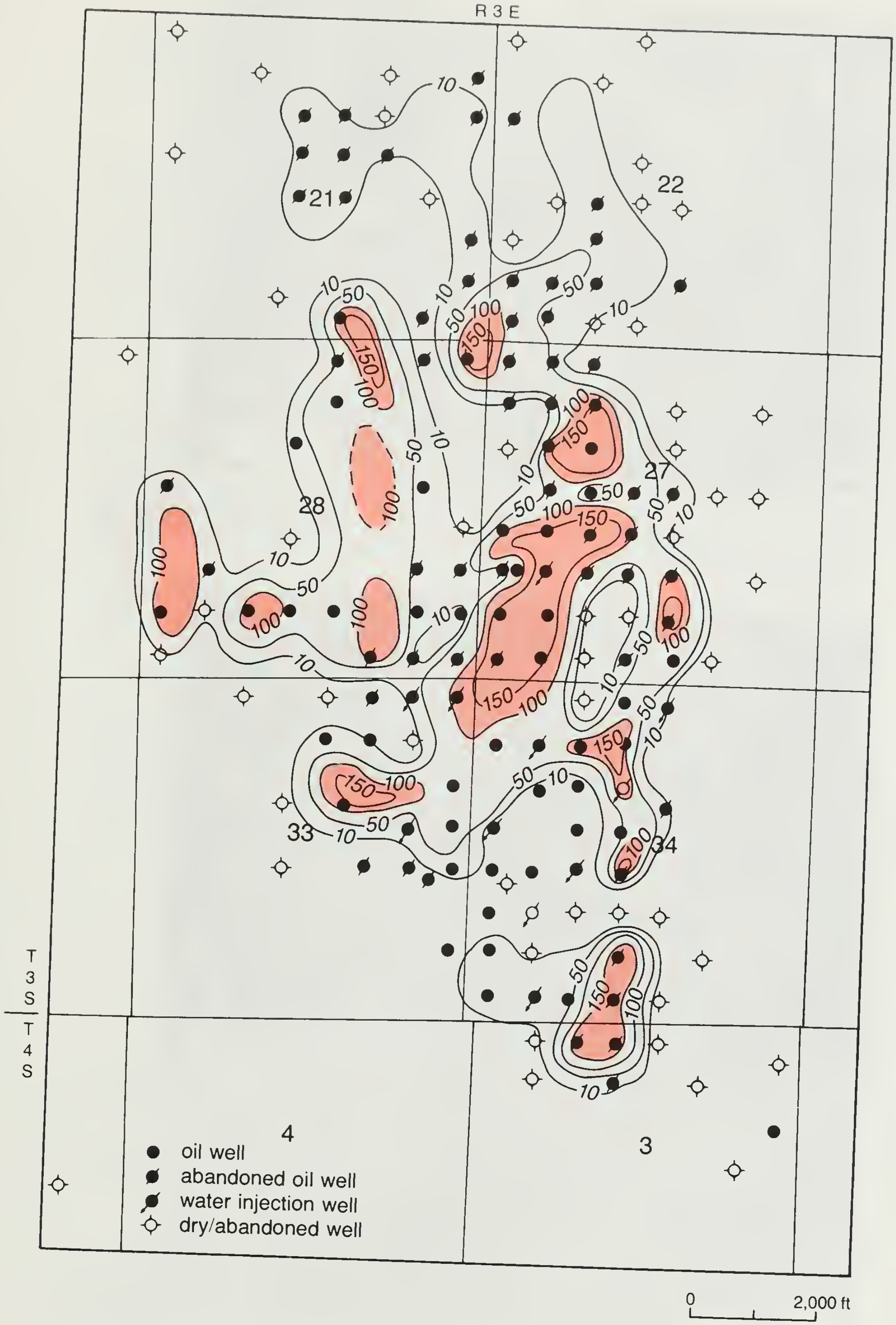


Figure 19 Results from the initial production test of wells completed from the Aux Vases at King Field (contour interval, BOPD). Areas that tested greater than 100 BOPD are highlighted.

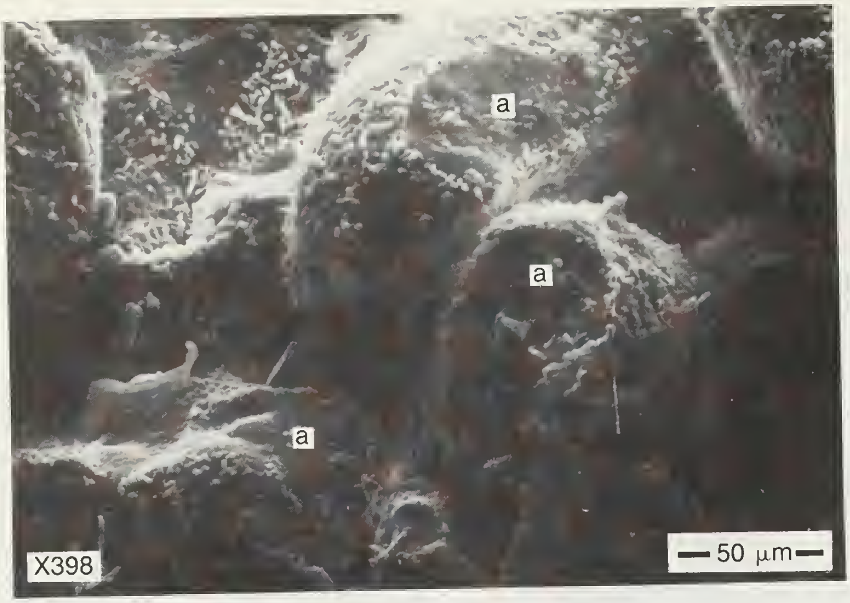


Figure 20 Scanning electron photomicrograph showing authigenic clay minerals coating detrital grains. Clay coatings are absent where there had once been grain-to-grain contact (a) (Lewis Production, State Game Farm No.1; 2,747 ft).

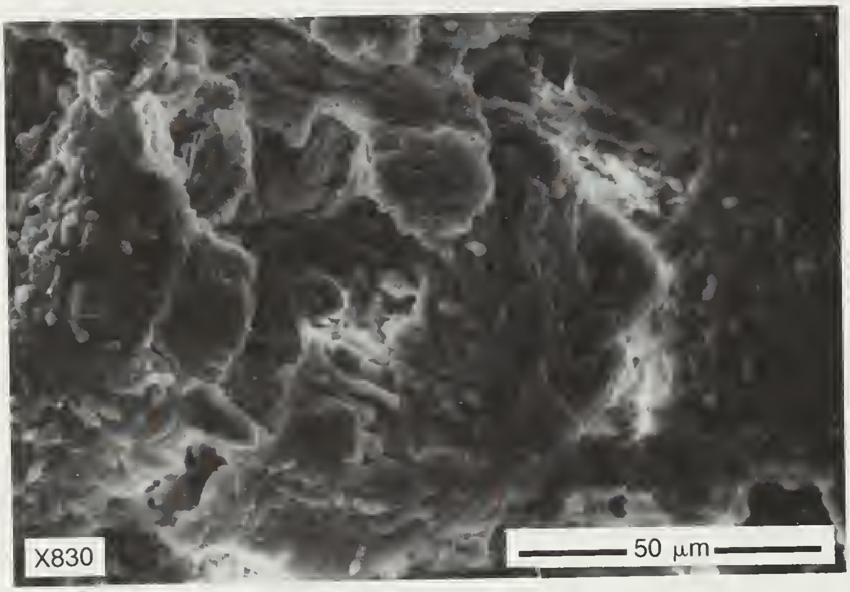


Figure 21 Scanning electron photomicrograph showing the dissolution of a potassium-rich feldspar grain (Lewis Production, State Game Farm No.1; 2,747 ft).

energy-dispersive X-ray do not seem to confirm these results; the chlorite samples do contain iron but not enough to categorize them as iron rich.

Two types of calcite cement are present in the Aux Vases at King Field. Type I calcite cement completely occludes all original porosity and is pervasive throughout the rock (plate 1). Type II calcite cement occurs as patches of randomly distributed pore-filling cement (plate 3). Some of the smaller patches of type II calcite cement apparently precipitated around whole and fragmented echinoderm grains (plate 3) and formed early in the diagenetic sequence. Not all of the type II calcite cement is early. For example, scanning electron microscopy analysis shows quartz cements have a coating of authigenic clay, whereas the calcite cements do not have this clay coating. This lack of clay coating suggests that calcite cement occurred after silica cementation. However, both type I and II cements may occur in early or late diagenesis.

Porosity Most of the effective porosity in the reservoir facies is primary. The two types of materials that make up the secondary porosity, in relatively minor amounts, are partially dissolved feldspars and microporosity associated with authigenic clay minerals. Micro- and macroporosity were created by the dissolution of feldspar grains. Partially dissolved feldspar grains can have a complex honeycombed texture (plate 4, fig. 21). Some of the feldspar grains are completely dissolved, leaving only an insoluble residue of clay rimming an open pore space (fig. 22). Dissolution may also occur after quartz and calcite cementation because neither of these cements was found in the micropores of these feldspars.

The filamentous illite (fig. 22) can reduce reservoir permeability (Almon and Davies 1981). Analysis by scanning electron microscopy did not show filamentous illite to be abundant, but the relatively minor amounts of filamentous illite seen in the Aux Vases reservoir may be an artifact of the drying method. All of the Aux Vases samples at King Field were air dried (they also had been in storage for more than 50 years), and after air drying, illite minerals tend to form a dense mat against the grain walls. Critical-point drying of samples retrieved immediately after drilling tends to preserve the illite morphology, giving more realistic results (McHardy and Birnie 1987).

An example of microporosity created by authigenic clays can be seen in figure 23a, in which iron-rich chlorite platelets (fig. 23b), about 5 µm wide, are oriented perpendicular to the grain surface. The actual grain surface in figure 23a is obscured by the clay platelets. The immobile water contained in the microporosity can result in anomalously high water saturation calculations when wireline logs are used (Kieke and Hartmann 1974); many of the apparently wet Aux Vases reservoir sands in the Illinois Basin produce little to no water (Seyler 1988). The clays also present

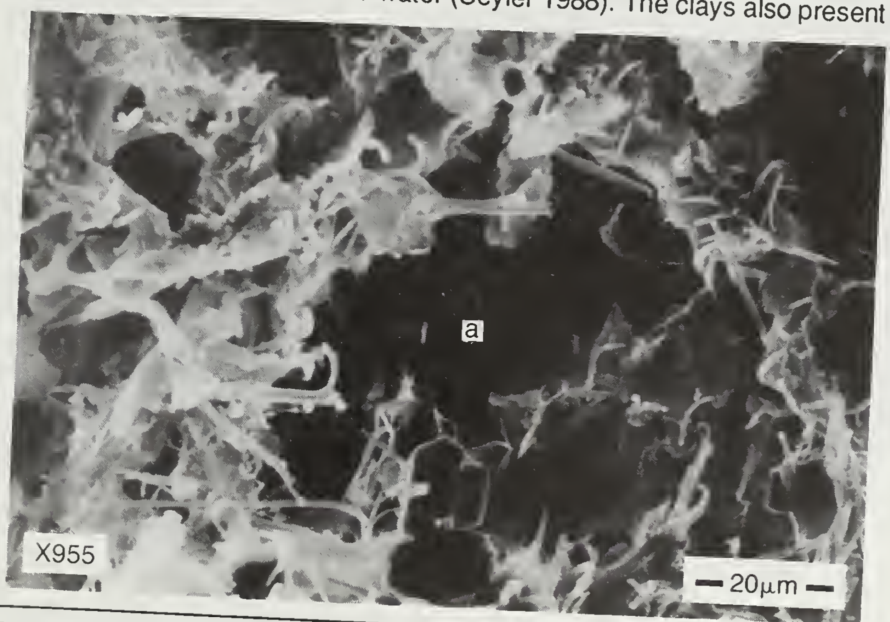
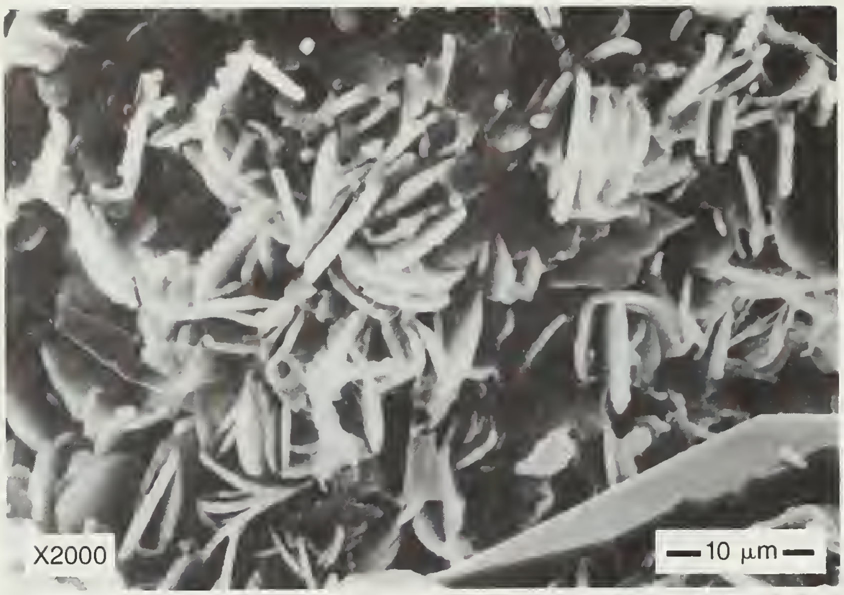
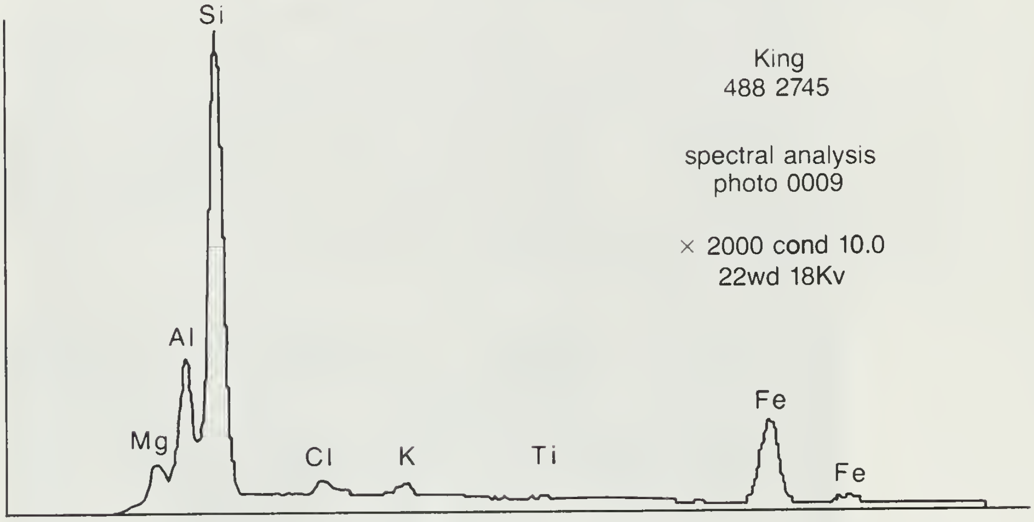


Figure 22 Scanning electron photomicrograph showing filamentous illite apparently forming around the original border of a dissolved grain of unknown origin, possibly a feldspar grain (a) (Gulf Ford No.1; 2,745 ft).



a



b

Figure 23 Clay platelets. (a) Scanning electron photomicrograph of clay platelets (chlorite) coating detrital grains. These clay platelets are oriented perpendicular to the grain face and therefore create abundant microporosity (Gulf Ford No. 1; 2,745 ft). (b) Energy-dispersive X-ray analysis indicates that the chlorite clays contain some iron.

a large internal surface area, which can impede enhanced oil recovery. Surfactants and polymer solutions injected into a formation can be adsorbed by clays (Ebanks 1987), forcing the use of greater amounts of reagents and significantly increasing the cost of the project.

Diagenetic history Sandstones in the Aux Vases at King Field have undergone a complex diagenetic history (fig. 24). The major events include (1) precipitation of calcite cement around echinoderm plates and fragments of plates, (2) formation of

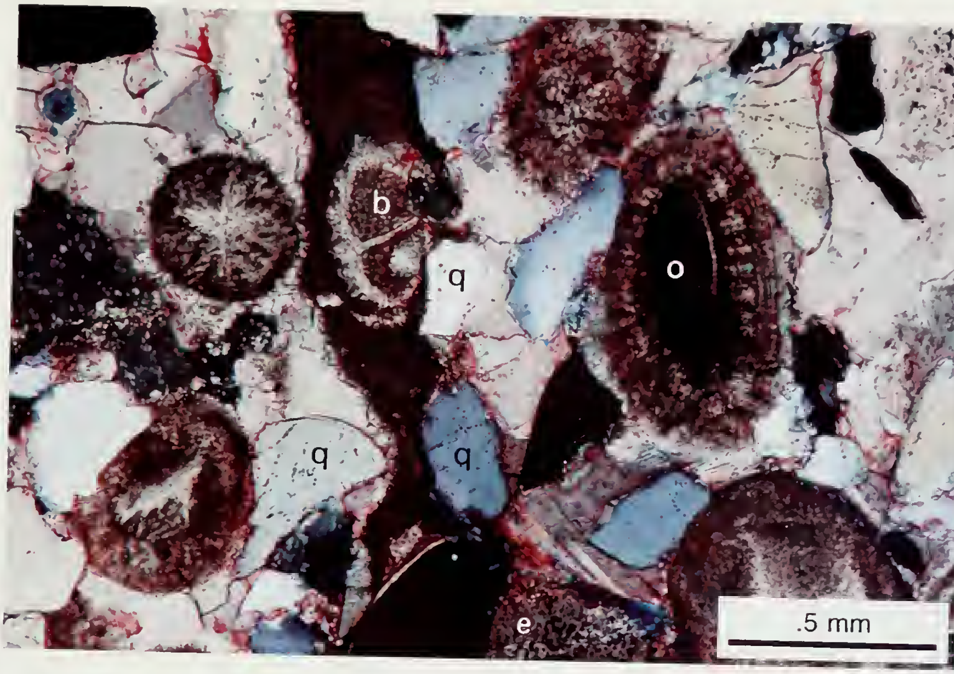


Plate 1 Photomicrograph of the limestone lithofacies. Note: ooid (o), quartz grains (q), echinoderm fragment (e), and probable bryozoan fragment (b) (Budiselich & Modert, L. Wallace No. 1; 2,733 ft).

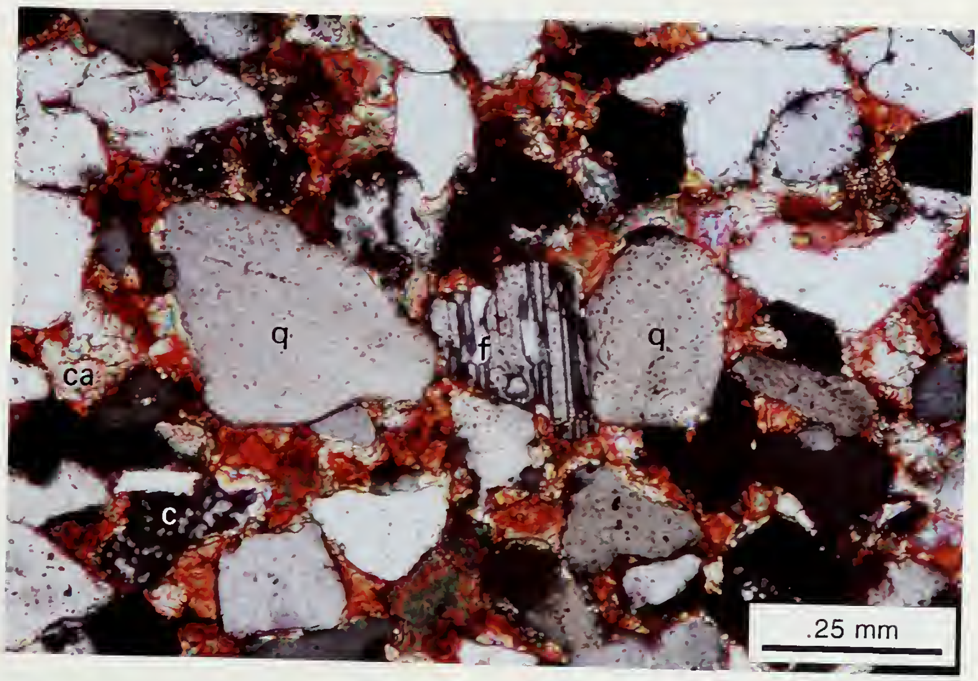


Plate 2 Photomicrograph showing porosity totally occluded by calcite cement (ca). Detrital grains are feldspar (f) and quartz (q). The chert (c) could be either authigenic or detrital (Gulf Ford No. 1; 2,732 ft).

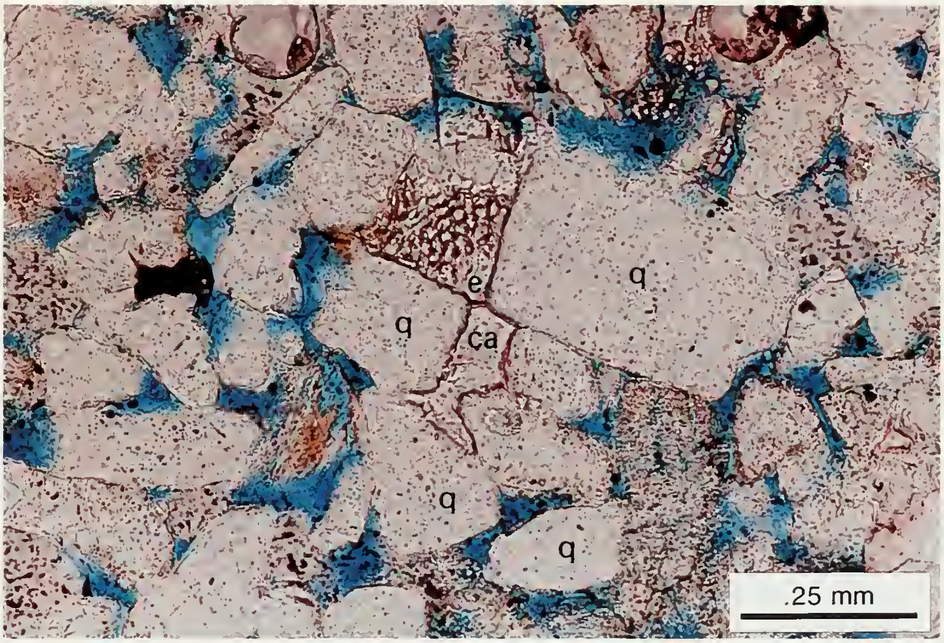


Plate 3 Photomicrograph of quartz grains (q) and calcite cement (ca) partly filling the pore space. In this instance, the calcite cement has precipitated around an echinoderm fragment (e) (Gulf Ford No. 1; 2,725 ft).

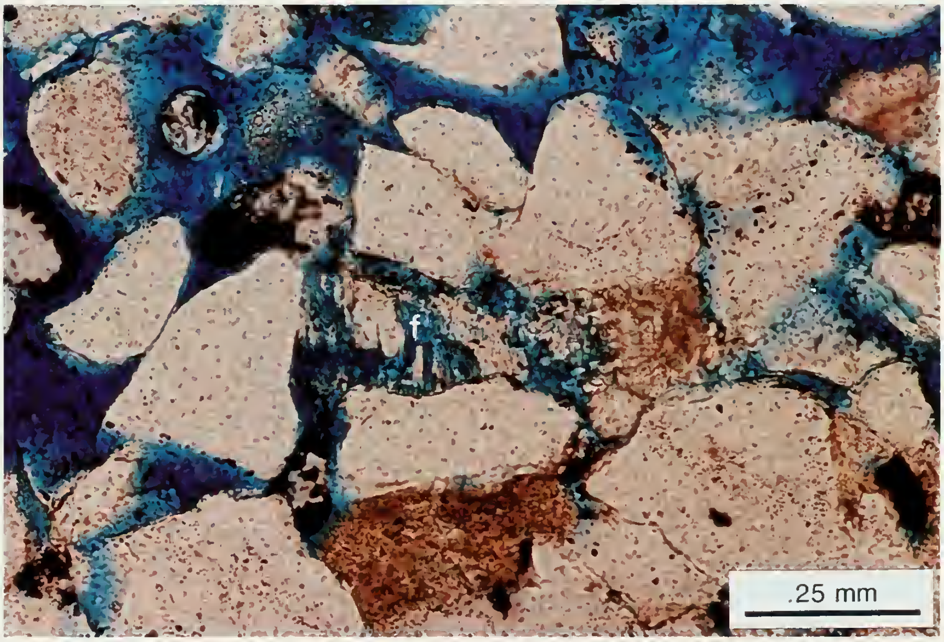


Plate 4 Photomicrograph of a degraded feldspar (f). Note the abundant microporosity and the honeycombed texture (Lewis Production, State Game Farm No. 1; 2,747 ft).

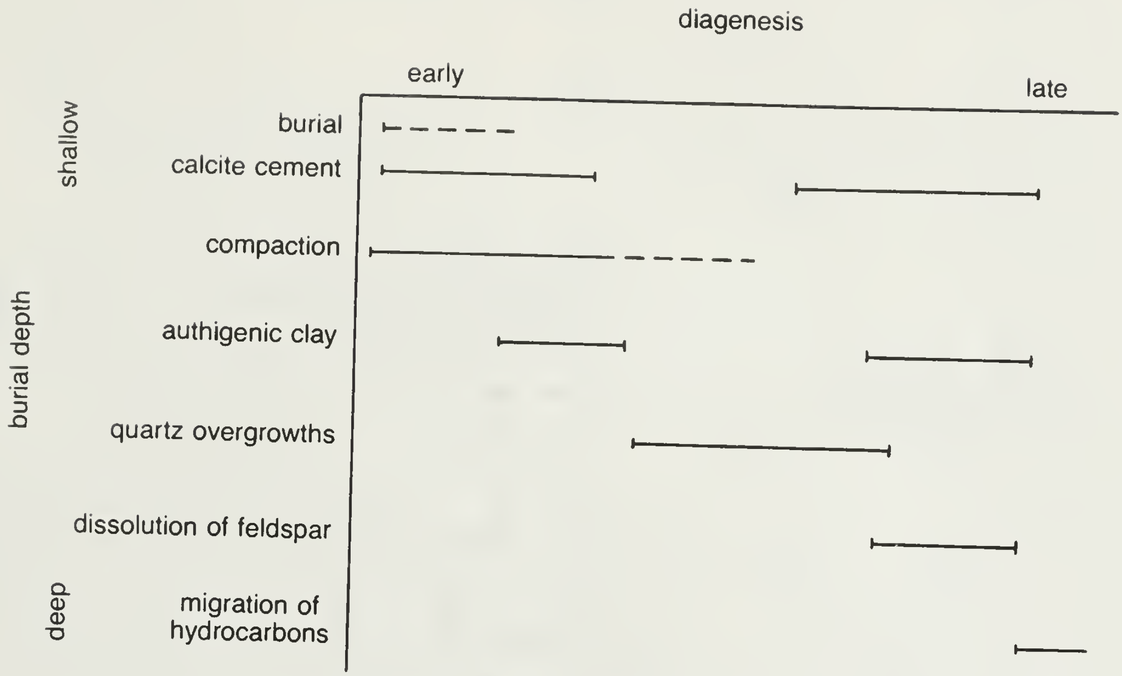


Figure 24 Diagenetic history of the Aux Vases at King Field.

authigenic clay, (3) quartz overgrowths, (4) dissolution of feldspars, (5) a second stage of authigenic clay and calcite cementation, and (6) the migration of hydrocarbons in the reservoir.

Porosity was reduced through cementation by carbonate minerals. Silica, in the form of overgrowths on detrital quartz grains, is also a significant factor in the reduction of porosity. Late-stage dissolution of feldspars created new but ineffective microporosity. Authigenic clay occurs as both an early and late diagenetic event. The early authigenic clay is beneficial, since it apparently inhibited the formation of quartz overgrowths. The later authigenic clay occludes the original porosity and also decreases permeability by clogging the pore throats.

PRODUCTION CHARACTERISTICS

Drilling and Completion Practices

Nearly all of the wells at King Field were drilled with a bentonite mud plus drill cavings suspended in freshwater. Many of the early wells in the field (pre-1950) were completed open hole, and casing was set just above the Aux Vases reservoir.

The standard early completion practice (before hydraulic fracture technology) for Aux Vases wells at King Field is typified by the Texas Company Bumpus No. 2 (fig. 25). It was completed by stimulating the Aux Vases sand with 20 quarts of nitroglycerine. On the initial production test in April 1943, this well began pumping 47 BOPD and no water from an open-hole completion at 2,720-57. In April 1954, 11 years later, the Bumpus No. 2 was producing 6 BOPD and no water. Because of the long sustained production at a fairly constant rate, this well was considered a good candidate for fracture treatment (comments from ISGS well file documents filed by Texaco). The well was fractured with 5,000 gallons of oil and 7,500 pounds

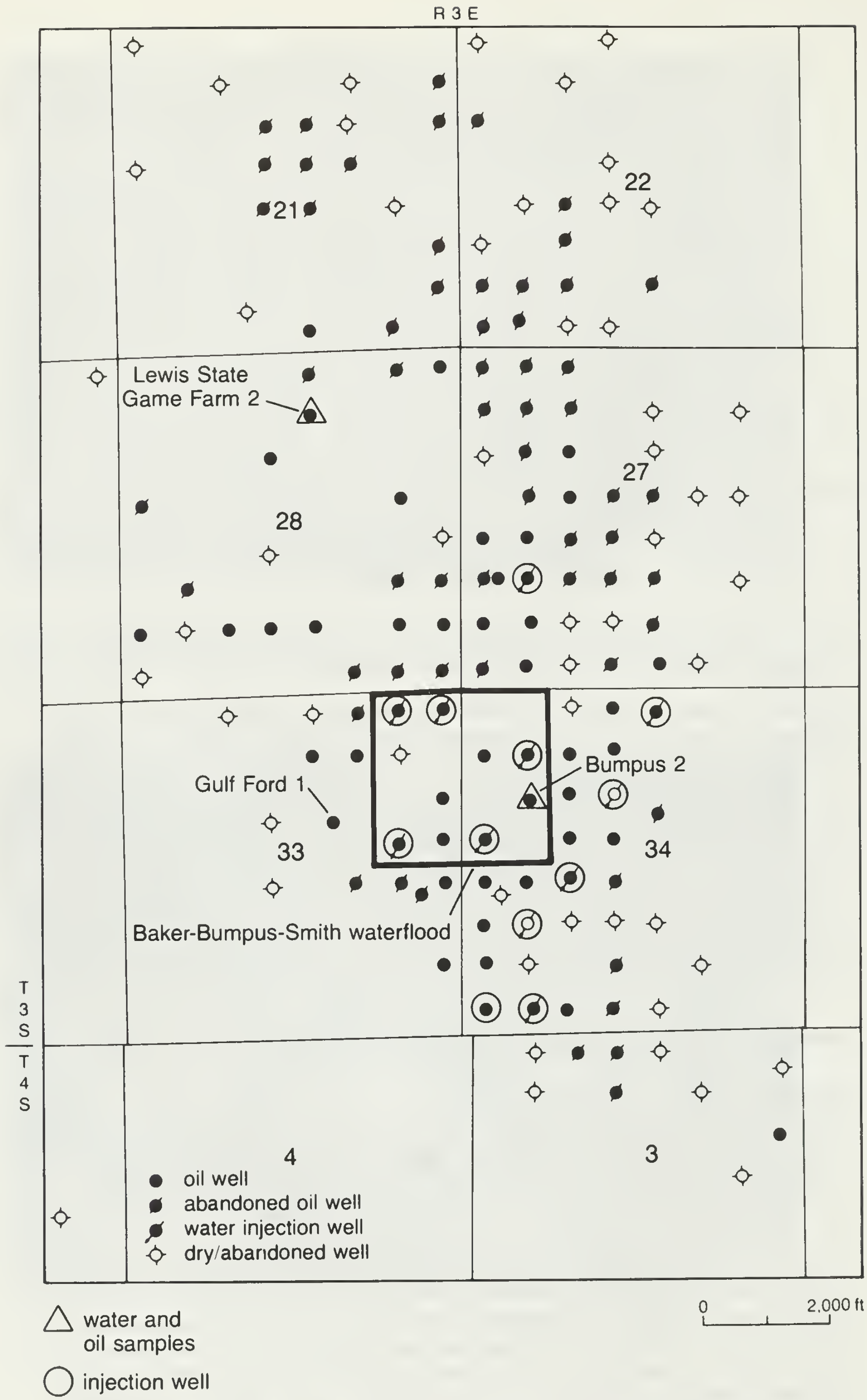


Figure 25 Map of King Field showing location of leases discussed in this report. Water injection wells have been circled. The two wells that have a triangle around the location have had both the oil and the water chemistry analyzed.

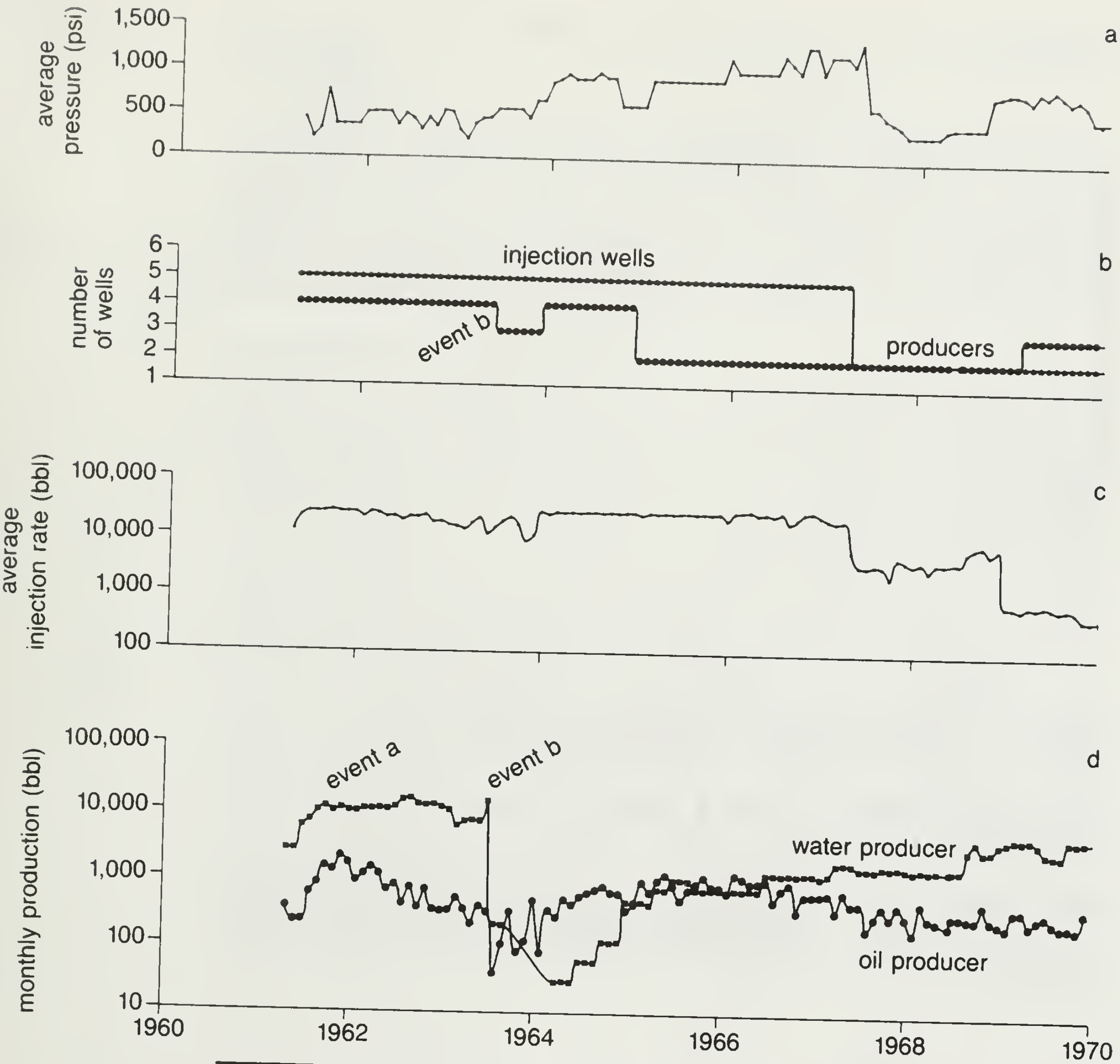


Figure 26 Waterflood information from the Baker-Bumpus-Smith lease at King Field.

of sand. After treatment, the well began producing at a rate of 104 BOPD with no water. Many of the other wells at King Field were fracture treated with similar results.

Results of Waterflooding

Waterflooding of the Aux Vases Sandstone at King Field was initiated in 1961. Four waterflood projects were established in the southern part of the field. No successful waterfloods were reported in the northern part of the field. In this section, I review the results of one waterflood and its favorable effect on oil production. The following analysis is an interpretation based on reported production data.

The first recorded waterflood at King Field was at the Texaco Baker-Bumpus-Smith unit (fig. 25). The flood was designed as a perimeter injection pattern with five injection and four producing wells (see analysis of the water chemistry of the produced water in appendix A). The injection water was a combination of 75 percent Pennsylvanian sand formation water and 25 percent produced water from nearby

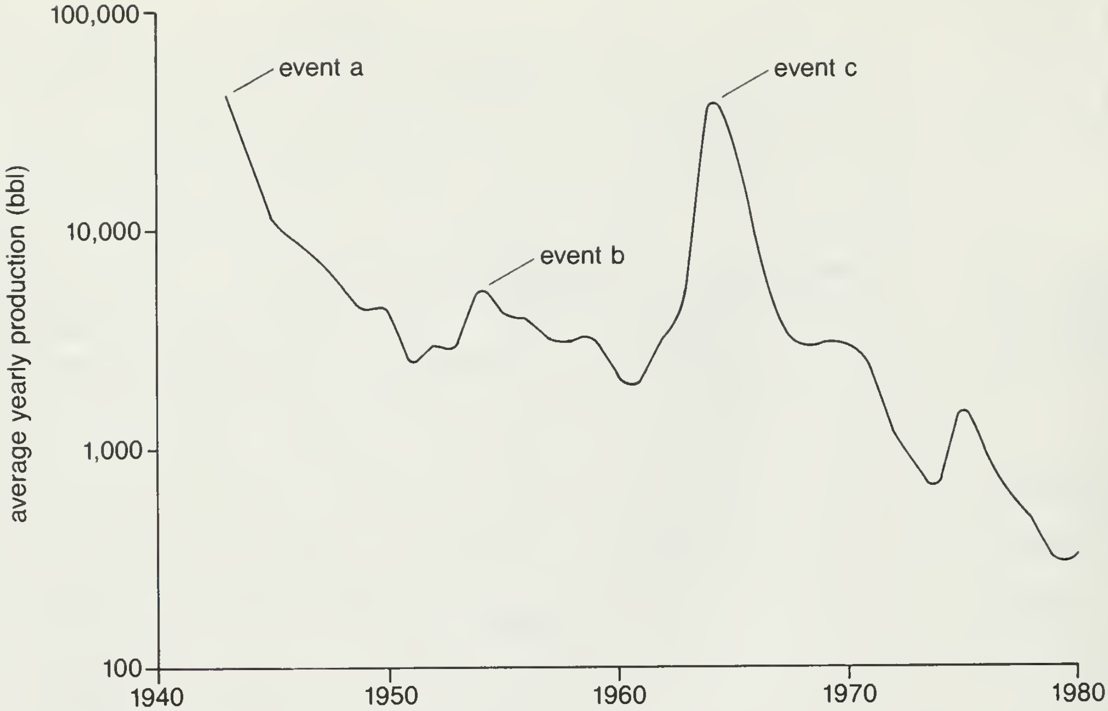


Figure 27 Decline curve for Ford No. 1 showing yearly production of oil from its discovery in 1943 until abandonment in 1980.

Aux Vases completions. Figure 26c,d depicts the production history of the first 9 years of this flood.

Before injection in early 1960, the unit was producing an average of 400 barrels of oil per month. Within 5 months of when injection was begun, production had increased to 1,300 barrels (fig. 26d, event a). Oil production began to decline in late

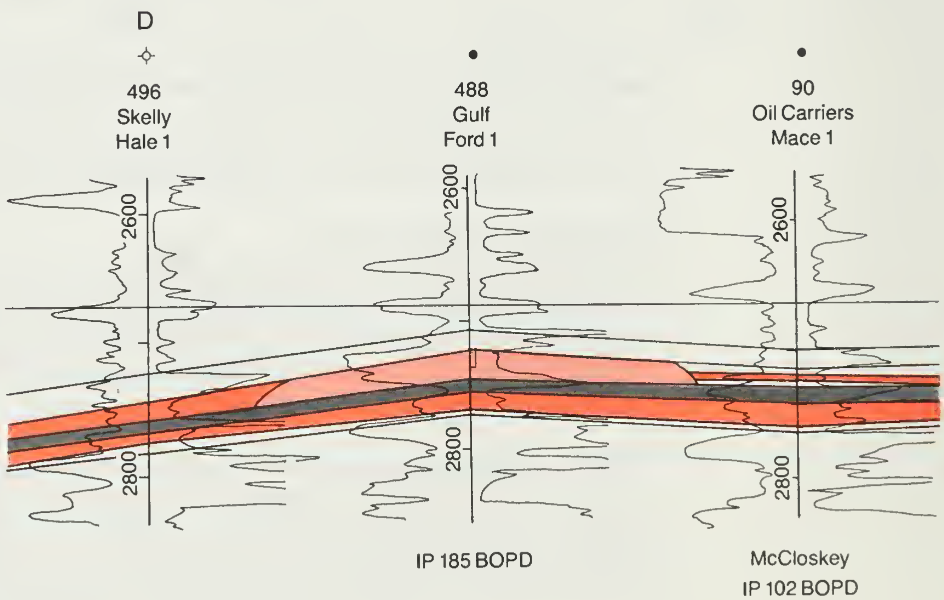


Figure 28 Cross section across the Gulf Ford No. 1 showing the lack of reservoir facies (location of this cross section is shown on fig. 10).

1966, but by the end of 1969, the unit was still producing more oil than before waterflooding.

Produced water from the Aux Vases increased from an initial 2,200 to more than 16,000 barrels of water per month. Most of this increase in water was from a single well, which in 1963 was abandoned (fig. 26c,d, event b); total water production decreased significantly. In 1964, water production began to increase because the injected water had reached additional producing wells. Average well head pressure recorded at the injection wells increased from 300 to more than 1,000 psi as the pore volume in the Aux Vases reservoir was filled with the injected water (fig. 26a).

The waterflood at the Baker-Bumpus-Smith lease also affected the production on adjacent leases. For example, the Ford No.1, located in the southwest part of King Field, less than 2,000 feet from an injection well, experienced increased production corresponding with waterflooding the Baker-Bumpus-Smith unit (fig. 25). The Ford No.1 was completed in 1943 in the Aux Vases sandstone by fracturing with 30 quarts of nitroglycerin and then acidizing with 1,500 gallons of acid; the initial production was 185 BOPD and no water. The Ford No.1 produced more than 40,000 barrels of oil in its first year of production (fig. 27, event a). During the next 10 years, production gradually declined to less than 3,000 barrels of oil per year. After hydraulic fracture treatment of this well in 1953, production increased to more than 4,000 barrels of oil per year (fig. 27, event b). In the early 1960s, production from the Ford No.1 increased from a low of 2,000 barrels of oil to a peak of 39,000 barrels of oil per year (fig. 27, event c). This nearly 20-fold increase in production was caused by the waterflood at the adjoining Baker-Bumpus-Smith Unit. As seen in figure 26c, Texaco was injecting more than 20,000 barrels of fluid into the Aux Vases and recovering less than half that amount of water. The porous reservoir sand encountered at the Ford No.1 grades to siltstone to the north, south, and west (fig. 28). The injected water from the Baker-Bumpus-Smith lease was constrained by these less permeable siltstones, and this is interpreted to have increased the effectiveness of the waterflood toward the Ford No.1 well.

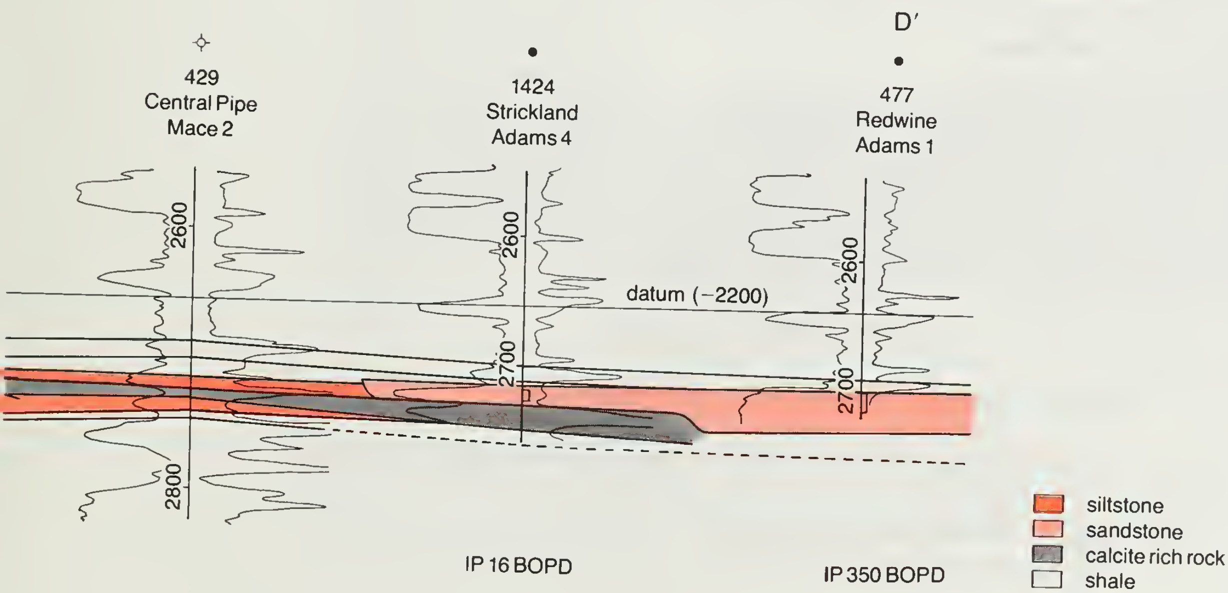


Figure 29 Total cumulative production of oil through time for Ford No. 1. The lower curve is the estimated production from only primary recovery. The upper curve is the actual production and combines both primary and waterflood recoveries.

Without the waterflood, the ultimate cumulative oil production is projected to have been about 170,000 barrels of oil and the Ford No.1 would have reached its economic limit by 1978 (fig. 29). After the adjacent waterflood, the cumulative production was 240,000 barrels. The waterflood apparently increased ultimate recovery in this well by more than 70,000 barrels of oil.

Original Oil in Place

A major objective of this study was to estimate the remaining mobile oil in place and the original oil in place (OOIP). A volumetric method was used to determine OOIP. For heterogeneous reservoirs, material-balance computations give OOIP values that are too low because the method fails to include all parts of the reservoir (van Everdingen and Kriss 1980). No reliable pressure data were available, and therefore the material-balance equation could not be used to calculate OOIP. The volume of the original oil in place (OOIP) in the reservoir is estimated by

$$\text{OOIP} = (7{,}758\, A\, h\, \varnothing)\,(1 - S_w) \qquad [1]$$

where
- 7,758 = conversion factor from acre-feet to barrels
- A = reservoir area in acres
- h = average reservoir thickness in feet and is identical to net sand isopach
- $\varnothing$ = average reservoir porosity
- S_w = average water saturation

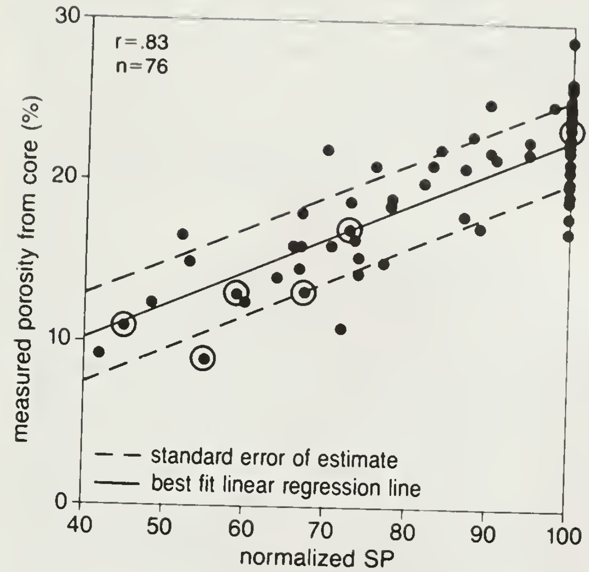


Figure 30 Measured porosity from core versus normalized SP for Franklin, Hamilton, Jefferson, and Wayne Counties, Illinois. Circled data are from King Field (modified from Leetaru 1990).

The oil volumes are converted to surface volumes [stock tank original oil in place (STOOIP)] by the formation volume factor:

$$\text{STOOIP} = \frac{\text{OOIP}}{B_{oi}} \qquad [2]$$

where B_{oi} = formation volume factor under original reservoir conditions (following standard industry convention, B_{oi} was assumed to be 1.15).

The most accurate method of determining porosity in older fields is from analyzing cores. Unfortunately, there was only one core analysis available from the better reservoir rock at King Field. Porosity was therefore estimated using the normalized SP (NSP) method (Leetaru 1990). This method has proven more effective in estimating porosity for the Aux Vases in Jefferson County than other methods used in old electric log analyses.

Core analyses from the better reservoir facies had an average porosity of 27 percent and an average permeability of more than 700 millidarcies (md). The Aux Vases reservoir at King Field has an NSP-porosity relationship that is similar to data from other fields in Franklin, Hamilton, Jefferson, and Wayne Counties (fig. 30). When both core analyses and the NSP method were used, the estimated porosity at King Field ranged from a low of 7 percent to a high of 27 percent. As shown in figure 30, the two lines drawn parallel to the regression line at a vertical distance equal to the standard error of estimate define a region that includes two thirds of the points from a given sample (Alder and Roessler 1960). The standard error of estimate for the NSP-porosity relationship is 2.6 percent porosity for these four counties.

The NSP cannot be greater than 100; therefore if the Aux Vases reservoir sandstone has an SP equal to or greater than the Cypress, it will equal 100 (Leetaru 1990). This limitation of NSP to values no greater than 100 implies that there will be a vertical clustering of values at NSP equal to 100.

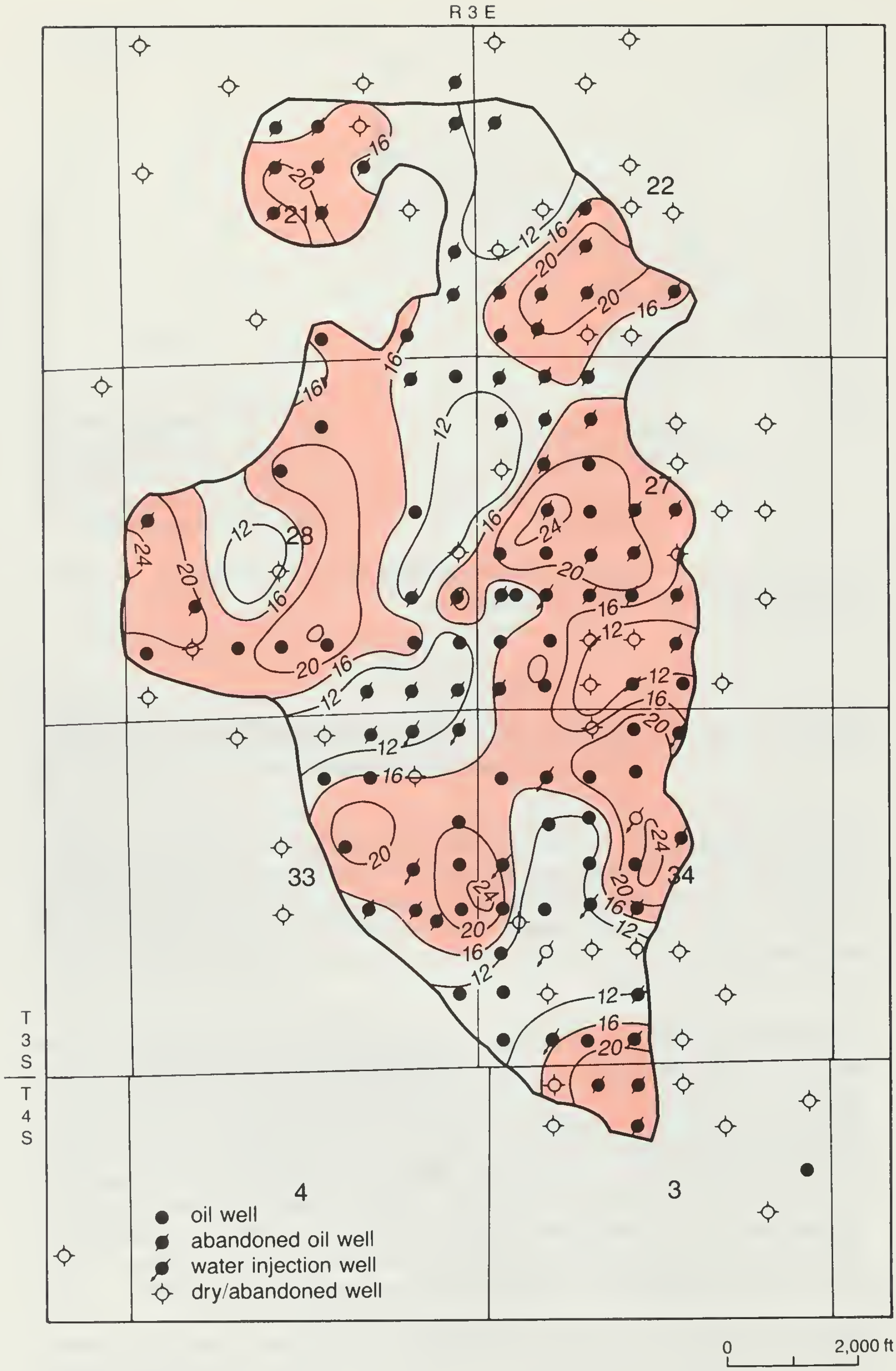


Figure 31 Map of calculated percent porosity of Aux Vases reservoir sand using the normalized SP method (contour interval, 4 ft). Areas with greater than 16 percent porosity are highlighted.

A computer-generated percent porosity map shown in figure 31 was used in the volumetric calculations. The estimated percent porosity was multiplied by the net sand thickness across the field (fig. 17) to get a porosity-net thickness map (fig. 32). This porosity-net thickness map was used in the final estimation of OO I P. The areal extent of the field as shown in figure 32 was defined by structural position and dry holes. Sandstones with estimated porosities of 11 percent or less and permeabilities of less than 5 md (Leetaru 1990) are not productive and were not used in OOIP calculations.

The reservoir volumetrics were calculated using a single average water saturation for the entire field. Water saturations are difficult to estimate in the Aux Vases Sandstone because of bound water in the abundant microporosity in the clays and degraded feldspars. Pickett plots or log-log plots of resistivity versus porosity are a graphic method of estimating water saturation of a formation. Pickett plot analysis of the sandstone intervals at King Field gives an average water saturation in the range of 40 to 50 percent (Leetaru 1990). The OOIP for the Aux Vases sandstone reservoir at King Field was between 15.8 and 18.9 million barrels of oil, assuming water saturations of 40 and 50 percent, respectively. The STOOIP was between 13.7 and 16.4 million barrels of oil. Industry commonly uses a recovery efficiency in the Aux Vases of 18 to 24 percent, which is typical of a solution gas reservoir. With a recovery efficiency of 22 percent, estimated primary recoverable reserves are between 3.0 and 3.6 million barrels. The actual primary recovery at King Field was about 3.5 million barrels of oil.

Remaining Oil in Place

The remaining recoverable reserves both primary and waterflood are calculated using the following equation.

$$\text{Remaining recoverable reserves} = (\text{STOOIP} \times \text{RE}) - \text{TPO} \qquad [3]$$

where STOOIP = stock tank barrels of original oil in place
TPO = total produced oil
RE = recovery efficiency

A numerical value for the recovery efficiency is difficult to estimate because of the reservoir heterogeneity of the Aux Vases. The recovery efficiency of the reservoir after primary recovery and waterflooding is considered by industry to be in the range of 30 to 40 percent of the STOOI P. If 16.4 million barrels of oil is a realistic value for STOOIP, then the remaining recoverable reserves are estimated to be between 1 and 2 million barrels of oil. Calculations done on individual leases at King Field indicate that 2 million may be closer to the actual value for ultimate mobile oil in place in the field.

DEVELOPMENT AND PRODUCTION STRATEGIES

Recommendation for Infill Drilling and Waterflooding

One objective of this study was to try to determine the maximum well spacing that will effectively drain the Aux Vases reservoirs. This objective was not accomplished. What is demonstrated here is that the current spacing does not effectively drain the reservoir. Barber et al. (1983) have shown that pay continuity calculations made before infill drilling are not accurate in heterogeneous reservoirs. The pay zones are

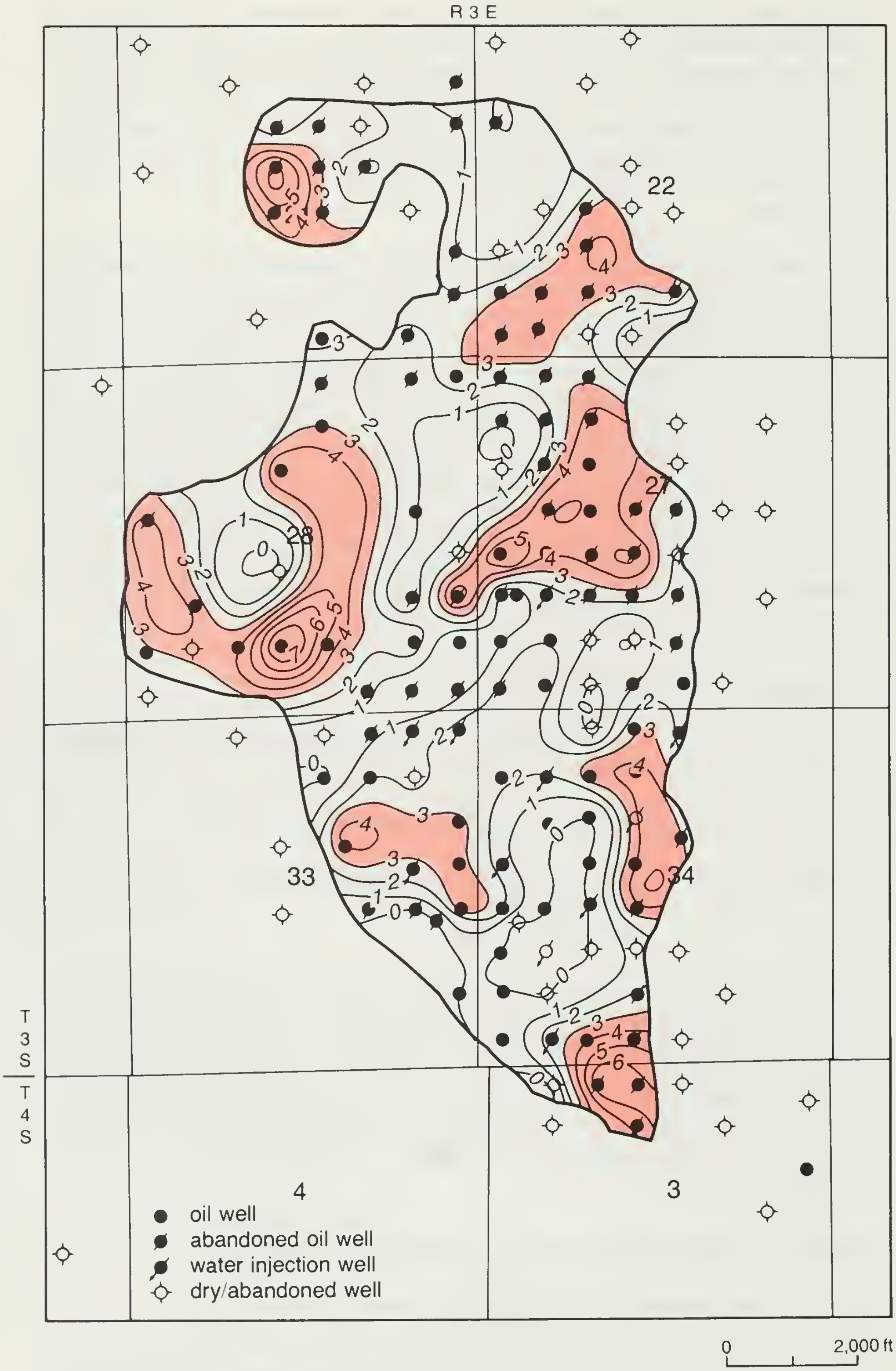


Figure 32 Porosity-net thickness map of the Aux Vases sand at King Field with an outline of the productive area of the field (contour interval, 1 ft). This outline was used as the area limits in the volumetric calculations. The light orange areas have a good potential for improved oil recovery through infill drilling and waterflooding. These high-potential areas have the thickest sand and the best porosity.

more discontinuous than is implied by widely spaced wells. This analysis probably holds true for the Aux Vases at King Field. Although the electric logs indicate that the sand is correlative, production tests, as listed on the scout ticket, show that many of these reservoirs are not in communication.

Discussion with members of the Illinois oil industry indicates that the actual results of waterfloods in the Aux Vases commonly do not match the expectations based on the geologic model (e.g., Bernard Podolsky, personal communication, Podolsky Oil, 1990). Water injected into the Aux Vases reservoir does not always go where planned. On the basis of waterflood effects on nonunitized wells, such as the Ford No.1, large areas of the Aux Vases at King Field probably are not swept by water.

A carefully planned infill program at King Field and at similar Aux Vases fields should be able to recover most of the remaining recoverable reserves. For a waterflood to be successful, the number of producers should be equal to or less than the number of injection wells (van Everdingen and Kriss 1980), and all of the wells should be drilled on a pattern that is based on geology. The injection wells should not be fracture treated (van Everdingen and Kriss 1980), because the mechanically induced fractures could cause channeling of the injection fluid. This type of careful development has not been done at King Field. Instead, the poorest producers were selected for conversion to injection wells. The injector-producer well pattern is semirandom; therefore, even those leases that have been subjected to waterflood may contain large amounts of unswept oil. Many of the converted injection wells had formerly been fracture treated.

Those areas with greater than 3 porosity-feet of Aux Vases pay should be considered first for a detailed, geologically targeted infill and waterflood program (fig. 32). An initial 5-acre infill spacing may be able to recover much of the unswept oil. Not enough data are available at this time to make an evaluation of the waterflood well pattern.

A selective infill drilling program has been used successfully in other areas. At Hewitt Field in Carter County, Oklahoma, an infill program was started in a field where the original spacing was 2.5 acres. A 15-well infill program was combined with a waterflood to recover an additional 400,000 barrels of oil (Barber et al. 1983).

Another example is Louden Field, located in Fayette and Effingham Counties, Illinois, which produces from Mississippian sandstones including the Aux Vases. A 50-well infill program was designed in conjunction with a waterflood to infill from the original 20-acre spacing to a 10-acre spacing. An additional 970,000 barrels of oil were recovered because of this program (Barber et al. 1983).

Clays and Potential Problems in Drilling, Completion, and Enhanced Oil Recovery

The pores of the Aux Vases sandstone are lined by three different types of clays. Of the three, mixed-layered illite/smectite and chlorite containing iron could cause the most significant problems. The mixed-layered illite/smectite is susceptible to swelling in freshwater (Almon and Davies 1981), which can clog pore throats and greatly reduce permeability. These mixed-layered illite/smectite clays are a potential problem when drilling with freshwater muds and during waterflooding. Smectite also readily adsorbs surfactants (Pittman 1989). Laboratory corefloods should be done first to determine the retention of surfactants by the Aux Vases clays before commencement of any field testing.

Chlorite that contains iron can be a problem when treated with hydrochloric acid. Iron is liberated from the clay by acid and reprecipitated as ferric hydroxide. The precipitate fills the pore throats and lowers the permeability of the reservoir (McLeod 1984). Iron removal can also remove the brucite layer from chlorite and produce a smectite-like clay in the process (Randall Hughes, personal communication, ISGS, 1990).

Formation damage in the Aux Vases Formation is a significant problem at King Field. All of the typical industry solutions for prevention of formation damage during drilling and completion of the well have restrictions. One solution to formation damage is fracture treating the reservoir. After hydraulic fracturing, the damaged areas are bypassed and the drainage area of the well is increased. I hypothesize that in the Aux Vases sandstones at King Field, possible swelling of the mixed-layered illite/smectite clays by fluids containing freshwater (both drilling muds and completion fluids) may be the reason that these wells have to be fracture treated.

RESERVOIR CLASSIFICATION

King Field is a combination structural-stratigraphic trap defined primarily by a large anticlinal structure. However, the stratigraphic component of this trap has significantly increased the compartmentalization of the Aux Vases into numerous distinct reservoirs. The Aux Vases was deposited in a tidal to subtidal mixed siliciclastic-carbonate nearshore shallow-marine system.

Weber and van Geuns's 1990 classification scheme would designate the depositional facies of the Aux Vases at King Field as a jigsaw puzzle to labyrinth-type reservoir. The significant characteristic of the jigsaw puzzle to labyrinth reservoir class is the lack of sand continuity. Sweep efficiency in a waterflood and the radius of drainage of individual wells are very low in this type of reservoir. In particular, the Aux Vases carbonate lithofacies forms impermeable barriers that laterally separate the sandstones into distinct compartments. The lenticular nature of the tidal channel and offshore sandstone lithofacies further increases the compartmentalization of the Aux Vases. This lack of lithologic continuity is illustrated by the difficulty in correlating electric logs.

CONCLUSIONS

The facies mosaic formed by the mixed carbonate and siliciclastic nearshore shallow marine system is the principal reason for the high degree of reservoir heterogeneity. The impermeable to poorly permeable siltstones, shales, and limestones of the offshore low-energy and tidal flat facies and the calcareous offshore high-energy facies separate the sandstones of the tidal channel-offshore bar facies into distinct reservoir compartments. The compartmentalization has resulted in an oil-water contact that is not at the same depth across the entire field. The complex lithology is also the cause of a number of dry holes on the structure. These wells did not encounter reservoir quality rocks.

The presence of mixed-layered illite/smectite can have detrimental effects on oil production. These clays can swell when in contact with freshwater and thereby reduce permeability. This could be a problem when drilling with freshwater and during waterflooding of the reservoir. Hydrochloric acid must be used with caution when injecting as a completion fluid because the iron minerals in the chlorite can precipitate and clog the pore throats.

The compartmentalization of the reservoir has allowed large areas of the Aux Vases reservoir at King Field to remain unswept by the waterflood projects. The original oil in place calculations indicate that there may be between 1 and 2 million barrels of oil still recoverable with a geologically targeted infill drilling program combined with additional well-designed waterflooding of the reservoir.

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REFERENCES

Aigner, T., 1985, Storm Depositional Systems: Springer-Verlag, New York, New York, 174 p.

Alder, H. L., and E. B. Roessler, 1960, Introduction to Probability and Statistics: W. H. Freeman & Company, San Francisco, California, 252 p.

Almon, W. R., and D. K. Davies, 1981, Formation damage and crystal chemistry of clays, *in* F. J. Longstaffer, editor, Clays and the Resource Geologist: Mineralogical Association of Canada Short Course, Calgary, Alberta, p. 81–103.

Barber, A. H., C. J. George, L. H. Stiles, and B. B. Thompson, 1983, Infill drilling to increase reserves—actual experience in nine fields in Texas, Oklahoma, and Illinois: Journal of Petroleum Technology, August, p. 1530–1538.

Bathurst, R.G.C., 1975, Carbonate Sediments and Their Diagenesis: Elsevier, New York, New York, 659 p.

Bell, A. H., M. G. Oros, J. Van Den Berg, C. W. Sherman, and R. F. Mast, 1961, Petroleum Industry in Illinois, 1960: Illinois State Geological Survey, Illinois Petroleum 75, 121 p.

Buschbach, T. C., and D. R. Kolata, 1990, Regional setting of the Illinois Basin, *in* M. W. Leighton, D. R. Kolata, D. F. Oltz, and J. J. Eidel, editors, Interior Cratonic Basins (World Petroleum Basins series): The American Association of Petroleum Geologists Petroleum, Tulsa, Oklahoma, p. 29–55.

Cole, R. D., 1990, The Stratigraphy, Petrology, and Depositional Environments of the Mississippian Aux Vases Formation Across the Southern Portion of the Illinois Basin: Ph.D. dissertation, Southern Illinois University, Carbondale, 260 p.

Ebanks, W. J., Jr., 1987, Geology in enhanced oil recovery, *in* R. W. Tillman and K. J. Weber, editor, Reservoir Sedimentology: Society of Economic Paleontologists and Mineralogists, Special Publication 40, p. 1–14.

Folk, S. H., and D. H. Swann, 1946, King Oil Field, Jefferson County, Illinois: Illinois State Geological Survey, Report of Investigation 119, 27 p.

Howard, R. H., 1990, Hydrocarbon reservoir distribution in the Illinois Basin, *in* M. W. Leighton, D. R. Kolata, D. F. Oltz, and J. J. Eidel, editors, Interior Cratonic Basins (World Petroleum Basin series): The American Association of Petroleum Geologists, Tulsa, Oklahoma, p. 299–327.

Kieke, E. M., and D. J. Hartmann, 1974, Detecting microporosity to improve formation evaluation: Journal of Petroleum Technology, August, p. 1080–1086.

Laporte, L., 1967, Carbonate deposition near mean sea-level and resultant facies mosaic: Manlius Formation (Lower Devonian) of New York State: American Association of Petroleum Geologists Bulletin, v. 51, p. 73–101.

Leetaru, H. E., 1990, Application of Old Electric Logs in Analysis of Aux Vases Sandstone (Mississippian) Reservoirs in Illinois: Illinois State Geological Survey, Illinois Petroleum 134, 21 p.

McHardy, W. J., and A. C. Birnie, 1987, Scanning electron microscopy, *in* M. J. Wilson, editor, A Handbook of Determinative Methods in Clay Mineralogy, Chapman and Hall, New York, New York, p. 174–208.

McLeod, H. O., Jr., 1984, Matrix acidizing: Journal of Petroleum Technology, December, p. 2055–2069.

Moore, D. M., and R. E. Hughes, 1990, The clay mineralogy of two Mississippian sandstone reservoirs in the Illinois Basin: Program with Abstracts, 27th Annual Meeting, Clay Minerals Society, Columbia, Missouri.

Pilkey, O. H., D. M. Bush, and R. W. Rodriguez, 1988, Carbonate-terrigenous sedimentation on the North Puerto Rico Shelf, *in* L. J. Doyle and H. H. Roberts, editors, Carbonate-Clastic Transitions, Developments in Sedimentology 42: Elsevier, New York, New York, p. 231–250.

Pittman, E. D., 1989, Problems related to clay minerals in reservoir sandstones, *in* J. F. Mason and P. A. Dickey, editor, Oil Field Development Techniques: Proceeding of the Daqing International Meeting, 1982: American Association of Petroleum Geologists Studies in Geology, no. 28, p. 237-244.

Pittman, E. D., and D. N. Lumsden, 1968, Relationship between chlorite coatings on quartz grains and porosity, Spiro Sand, Oklahoma: Journal of Sedimentary Petrology, June, p. 668–670.

Potter, P. E., 1962, Late Mississippian Sandstones of Illinois: Illinois State Geological Survey, Circular 340, 36 p.

Samson, I. E., and S. B. Bhagwat, 1989, Illinois Mineral Industry in 1987: Illinois State Geological Survey, Illinois Mineral Notes 101, 43 p.

Seibold, E., L. Diester, D. Futterer, H. Lange, P. Muller, and F. Werner, 1973, Holocene sediments and sedimentary processes in the Iranian part of the Persian Gulf, *in* B. H. Purser, editor, The Persian Gulf: Springer-Verlag, New York, New York, p. 57–80.

Selley, R. C., 1978, Ancient Sedimentary Environments: Cornell University Press, Ithaca, New York, 287 p.

Seyler, B. J., 1988, Role of clay mineralogy in water saturation: drilling, completion, and recovery techniques, *in* C. W. Zuppann, B. D. Keith, and S. J. Keller, editors, Geology and Petroleum Production of the Illinois Basin, volume 2: Indiana-Kentucky and Illinois Geological Societies Joint Publication, p. 150.

Swann, D. H., 1963, Classification of Genevievian and Chesterian (Late Mississippian) Rocks of Illinois: Illinois State Geological Survey, Report of Investigation 216, 91 p.

Swann, D. H., and A. H. Bell, 1958, Habitat of oil in the Illinois Basin, *in* L. G. Weeks, editor, Habitat of Oil: American Association of Petroleum Geologists, Tulsa, Oklahoma, p. 447–472.

Thomson, A., 1982, Preservation of porosity in the deep Woodbine/Tuscaloosa trend, Louisiana: Journal of Petroleum Technology, May, p. 1156–1162.

van Everdingen, A. F., and H. S. Kriss, 1980, A proposal to improve recovery efficiency: Journal of Petroleum Technology, July, p. 1164–1168.

Wafer, J. O., 1955, An electric log study of structure, thickness and permeability of the Aux Vases Formation, Mt. Vernon, Illinois Area: M.S. thesis, University of Illinois, Champaign, 30 p.

Weber, K. J., 1982, Influence of common sedimentary structures on fluid flow in reservoir models: Journal of Petroleum Technology, March, p. 665–672.

Weber, K. J., and L. C. van Geuns, 1990, Framework for constructing clastic reservoir simulation models: Journal of Petroleum Technology, October, p. 1248–1253, 1296–1297.

Willman, H. B., E. Atherton, T. C. Buschbach, C. Collinson, J. C. Frye, M. E. Hopkins, J. A. Lineback, and J. A. Simon, 1975, Handbook of Illinois Stratigraphy: Illinois State Geological Survey, Bulletin 95, 261 p.

Wilson, B. J., 1985, Depositional environmental and diagenesis of sandstone facies in the Aux Vases Formation (Mississippian), Illinois Basin: M.S. thesis, Southern Illinois University, Carbondale, 130 p.

APPENDIX A RESERVOIR FLUID ANALYSIS

API number 1208100498
Operator Baldridge Oil
Well name Bumpus No. 2
Location T3S R3E Sec. 34 SW NW
County Jefferson County
Field name King Field
Producing formation Aux Vases
Perforation depth (ft) 2,720 to 2,739
Surface elevation (ft) 469 (drilling floor)
Waterflooded yes

Brine Analysis
Brine sample number EOR-B8
Temperature (°C) 20.8
Resistivity without ATC, 0.0649 ohm-m (estimated from Na data)
Eh (mV) 238
pH 6.35
Comment high gas; not enough oil for sampling (%)

Anion chemistry (in mg/L)*

Br	NA	I	NA
Cl**	79,485	NH_4	NA
CO_3	NA	NO_3	NA
HCO_3	NA	SO_4	NA

*NA, not analyzed.
**Estimated from Na data.

Cation chemistry (in mg/L, unless noted)

Al	2.5	Cr	NA	Na	46.0 g/L	Sr	173
As	NA	Cu	NA	Ni	0.15	Ti	NA
B	3.8	Fe	5.7	Pb	<0.4	Tl	<0.4
Ba	0.49	K	205	Rb	NA	V	NA
Be	NA	La	<0.01	Sb	NA	Zn	<0.02
Ca	3,260	Mg	1,260	Sc	<0.01	Zr	0.08
Cd	<0.05	Mn	0.62	Se	NA		
Co	<0.07	Mo	<0.08	Si	4.68		

Oil Analysis
Oil sample number EOR-O8

Sara analysis

saturates	56.2%
aromatics	11.7%
resins	13.5%
asphaltenes	1.4%
"lost"*	17.2%

*highly volatile compounds and compounds adsorbed by chromatography column.

Selected hydrocarbon ratios

C17/C18	1.08
pristane/phytane	1.80
C17/pristane	1.21
C18/phytane	2.02

Comment interpreted to be Devonian oil

APPENDIX A (cont.)

API number 1208100167
Operator Baldridge Oil
Well name State Game Farm A-2
Location T3S R3E Sec. 28 NW NE
County Jefferson County
Field name King Field
Producing formation Aux Vases
Perforation depth (ft) 2,744 to 2,752
Surface elevation (ft) 492 (drilling floor)
Waterflooded possibly not effected by flood

Brine Analysis
Brine sample number EOR-B9
Temperature (°C) 17.8
Resistivity 0.0621 ohm-m
Eh (mV) 287
pH 6.81
Comment high gas

Anion chemistry (in mg/L)

Br	180	I	3.9
Cl	85,000	NH_4	36
CO_3*	<1	NO_3	0.06
HCO_3	120	SO_4	72

*as $CaCO_3$.

Cation chemistry (in mg/L, unless noted)

Al	0.3	Cr	<0.07	Na	48.50 g/L	Sr	199
As	<0.5	Cu	<0.05	Ni	<0.1	Ti	0.04
Ba	0.75	Fe	<0.06	Pb	<0.4	Tl	<0.4
Be	<30 g/L	K	280	Rb	NA	V	<0.08
B	3.4	La	<0.01	Sb	<0.3	Zn	<0.02
Ca	4,710	Mg	1,720	Sc	<0.01	Zr	<0.02
Cd	<0.05	Mn	0.56	Se	<0.7		
Co	<0.07	Mo	<0.08	Si	4.4		

Oil Analysis
Oil sample number EOR-O9

Sara analysis

saturates	50.3%
aromatics	8.4%
resins	8.0%
asphaltenes	2.8%
"lost"	30.5%

Selected hydrocarbon ratios

C17/C	181.04
pristane/phytane	1.80
C17/pristane	1.20
C18/phytane	2.06

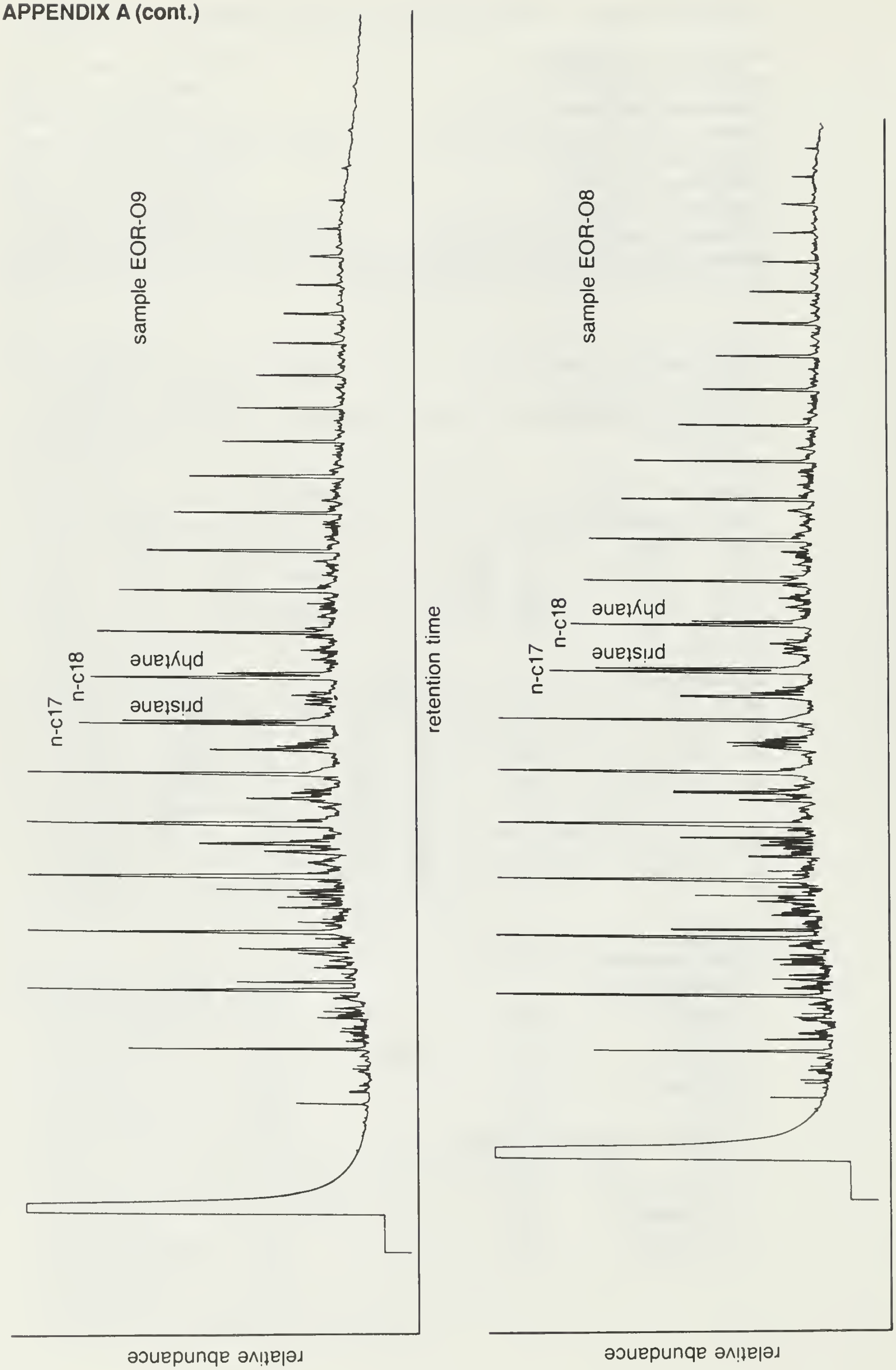

Figure A1 Gas chromatograms of saturated hydrocarbons of oil from the Aux Vases Formation, King Field.

APPENDIX B MINERAL COMPONENTS FROM X-RAY DIFFRACTION ANALYSIS

API number	Depth (ft)	Clay Index	%I	%I/S	%C	%Q	%Kf	%Pf	%CC	%D
081496	2,736	0.08	4	3	tr	81	11	tr	0	0
081496	2,739	0.39	22	13	3	30	2	2	15	12
081496	2,744	0.40	19	16	5	57	2	1	0	0
081488	2,725	0.11	5	4	2	69	14	6	tr	0
081488	2,732	0.04	2	1	1	73	2	3	18	0
081488	2,738	0.06	3	2	2	64	16	2	12	tr
081488	2,745	0.02	tr	1	1	77	1	5	14	0
081488	2,746	0.02	1	1	tr	21	1	1	75	0
081488	2,748	0.08	3	4	1	36	1	8	47	0
081488	2,750	0.01	tr	tr	1	66	2	1	30	0
081490	2,732	0.06	2	1	3	77	3	1	12	tr
081090	2,722-27	0.18	8	5	6	72	3	3	3	0
081090	2,747-48	0.15	6	4	5	63	tr	3	18	tr
081459	2,735	0.03	1	tr	3	93	tr	tr	3	0
081374	2,747	0.09	3	2	4	81	3	2	5	0
081374	2,750	0.02	1	1	1	76	1	2	19	0
081496	2,736	0.08	4	4	tr	81	11	tr	0	0

Abbreviations: I, illite; I/S, mixed layer illite/smectite; C, chlorite; Q, quartz; Kf, potassium feldspar; Pf, plagioclase feldspar; CC, calcium carbonate; D, dolomite; tr, trace.

$$\text{clay index} = \frac{4 \times 020 \text{ clay peak (19,920)}}{\text{adjusted sum nonclay peaks}}$$

RESERVOIR SUMMARY

Field King Field
Location Jefferson County, Illinois
Tectonic/Regional Paleosetting Illinois Basin
Geologic Structure anticline
Trap Type structural stratigraphic
Reservoir Drive gas depletion drive
Original Reservoir Pressure unknown
Reservoir Rocks
  Age Upper Valmeyeran Series of the Mississippian System
  Stratigraphic unit Aux Vases Formation
  Lithology sandstone
  Wetting characteristics (oil/water) NA
  Depositional environment mixed siliciclastic-carbonate nearshore
  Productive facies tidal channel offshore bar
  Petrophysics (∅, *k* from unstressed conventional core; S_w from logs)
    Porosity type ∅total = 18%: primary, NA; secondary, NA
    ∅ Average 18%, range 7 to 27%, cutoff 11%
    k air NA
    k liquid NA
    S_w 45%
    S_{or} NA
    S_{gr} NA
    Cementation factor 1.7
Source Rocks
  Lithology and stratigraphic unit New Albany (Devonian) Shales
  Time of hydrocarbon maturation NA
  Time of trap formation NA
Reservoir Dimensions
  Depth (absolute and subsea) 2,750 (2,250) feet
  Areal dimensions 1,700 acres
  Productive area 1,700 acres
  Number of pay zones 4
  Hydrocarbon column unknown
  Initial present fluid contacts no clear oil/water contact
  Average net sand thickness 15 feet
  Average gross sand thickness NA
  Net/gross NA
  Initial reservoir temperature
  Fractured natural, NA; artificial (type), NA
Wells
  Spacing 10 acre
  Pattern NA
Total 163: producer, 108; dry holes, 55
Reservoir Fluid Properties
  Hydrocarbons
    Type NA
    Gas/oil ratio NA
    API gravity NA
    Formation volume factor 1.15
    Viscosity NA
    Bubble point pressure NA
  Formation water
    Resistivity NA
    Total dissolved solids (ppm) NA

Volumetrics

In-place 17 million barrels of oil (MMBO)

Cumulative production 4.1 MMBO

Ultimate recovery primary, 3.5 MMBO; secondary, 0.6 MMBO

Additional recovery from infill drilling and secondary 2.5 MMBO [secondary (incremental), NA; tertiary (incremental), NA]

Recovery efficiency (factor) primary, 22%; secondary, 18%; tertiary, NA

Typical Drilling/Completion/Production Practices

Completions open hole, NA; cased, NA

Drilling fluid bentonite

Fracture treatment 5,000 gallons of oil and 7,500 pounds of sand

Acidization NA

Other NA

Producing mechanism

Primary (indicate any period of flow) gas depletion

Secondary waterflood

Tertiary NA

Typical Well Production (to date)

Average daily 80 bbl

Cumulative 38,000 bbl

Water/oil ratio (initial/cumulative) NA

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